Life cycle analysis of transparent building elements

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SCHOOL OF SCIENCE & TECHNOLOGY

A thesis submitted for the degree of

Master of Science (MSc) in Energy Systems

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THESSALONIKI – GREECE

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Abstract

This dissertation was written as a part of the MSc in Energy Systems at the International Hellenic University. It focuses on the environmental performance of four widely used frame materials in the market: aluminum, PVC, wood and wood-metal, all sealed with a double-glazed unit, which are very common in construction sector. Life cycle assessment is the method used to analyze and examine the environmental burdens of each frame case respectively, taking into account production, disposal and transportation of the materials used for the manufacturing of those window systems. The continuous growing of environmental concern and the direction of protective policies are the motivations for such studies.

The SimaPro 7 LCA software was used and the CML 2 baseline assessment method was applied to evaluate windows performance. The data needed for the analysis is taken from previous studies, industrial reports and Ecoinvent database if no other source is available. Ten impact categories were grouped and identified to assess the environmental performance of windows, scale-based on CML2 method and followed by all relevant characterization and damage factors. Finally the results were compared to conclude with useful and reliable as possible information for decision makers.

To this point I would like to note what a great pleasure for me was to undertake such an interesting and up to date subject. I would like to thank my family and friends for their support, especially Benjamin Christiaens who as a friend contributed the most and helped to fulfill this thesis. Finally I would like to extremely thank my supervisor Dr. Dimitrios Anastaselos for the whole cooperation and assistance in all sectors of my study.

Keramidas Alexandros

29/10/2012

Contents

1. Introduction

In recent years, the increase in consumption of raw materials, the energy use and the depletion of natural resources rang the bell of the environmental awareness of the general public, industries and governments. Extensive number of studies emerged the seriousness of the situation about the continuous expansion of the environmental impacts and the depth of anthropogenic effects, underlying the need to apply environmental movement in all possible ways.

Construction sector is one of the most energy intense which on a global scale counts for more than 40% of inorganic material(sand, gravel, lime) and more than 25% of wood been used for projects[1]. More than 55% of the EU capital is being invested in construction projects, highlighting the huge magnitude of this sector on the socio-ecological relationship.

Legislatures have established protection policies of the environmental values, businesses have adopted certification schemes and eco-labels for the products or services being provided and consumers have performed friendly attitude of varying information and fairness.

The development of production companies has grown rapidly providing a huge number of products, processes or activities, while the efforts to apply policies for sustainability increased the interest of the society and the industry parts in issues that are related to the environment. Numerous actions have emerged by the industrial section for minimizing the environmental impacts of their utilities and provide more “green products” using more “green processes”. This led to research of methods to identify the most critical aspects of their production lines and control ways to limit their environmental impacts with more efficient products than the previous ones. In this field, various tools were developed and control standards were applied to assess the environmental performance of the companies.

Life-Cycle-Analysis (LCA) is a useful tool approach for assessing the overall environmental impact of a product through all stages of its life cycle from raw material extraction to manufacturing, use, maintenance, recycling and disposal at the end of the service life, while all emissions to air, water and land are considered. It is a structured analytical method that is gaining ground day by day from all sectors for recognizing impacts caused by complex systems, like buildings in the construction sector.

To mitigate the environmental impacts of buildings, certification schemes, rating systems and eco-labeling for the design, construction and operation of sustainable buildings have emerged and grown in acceptance, with the argument that LCA methodology should be incorporated in the building's rating and certification systems.

As a building is a unique and complex system of interrelated components and subsystems, it is difficult to evaluate the environmental consequences of a specific building design.

There are many products and numerous materials to be assessed separately for the better understanding of building’s performance. In this study the interest is focused on the environmental performance of the window systems.

1.1. THE WINDOW CASE

Windows account for 10-25% [2] of the building's total external surface, providing a variety of functions as part of the buildings envelope. The most important contribution of windows to buildings is to incorporate daylight and fresh air, provide sufficient outdoor optical view, and maintain interior environment at desirable comfort conditions.

Windows consist of different materials and are available for various uses (residential, commercial buildings) in a wide range of designs and in any desired size. The primary components that comprise a window are: the glazed unit, frame and sash. The glazed unit may consist of one, two or in some colder countries even three glaze panes with various additives(films/coatings) that help to improve the overall performance of the window. Some inert gases are available to fill the mid parts of the glazing units to provide better insulation characteristics of the window. The frame materials can be wood, polyvinyl chloride (PVC), aluminum, fiberglass, wood composites or a combination of them. Windows can be operable or fixed, depending on the functionality of the casement. Operable windows can turn, tilt and switch position in vertical or horizontal slider, depending on the preferences of the user. They have a fairly long life and are highly contributing to the heat losses in the residential buildings. Therefore, there have been technological advances in the design and manufacturing of windows to improve their performance. As windows are an important element in the design of a building, it is crucial to understand and evaluate the environmental consequences of different window types.The most critical fields to investigate is the construction phase of the window corresponding to stages from extraction of raw materials to the assembly of the window (cradle to gate), and the use-phase alternatively known as service-life. It is widely known that the use phase of a window is the most energy intense with extensive heat-losses during their lifetime and there is no meaning in direct comparison between this phase and any others during the life-cycle of windows. Windows are also expected to be durable and economical with the least possible cost to prospective owners.

1.2. ENERGY RATING WINDOWS

Several countries have made serious efforts to develop energy rating systems for windows and establish energy labels, aiming to inform the consumers about the energy performance of comparable windows by indicating the possible savings compared to a reference one.USA, Canada, Australia, New Zealand and Europe have some of the most currently developed rating systems and certification programs regarding the energy performance of windows. Through these systems, manufacturers around the world try to rate and launch their products in the market as environmentally friendly "green products", showing the advantages compared to the alternatives and raising this way the interest of consumers.

In USA, the National Fenestration Rating Council (NFRC), developed a rating system of the thermal performance of residential fenestration products, including windows. Three main

characteristics been assessed through this program are: thermal transmittance (U-factor), solar heat gain coefficient and air infiltration using ASHRAE's standardized data.
Canada's rating system (CRS), is very similar to NFRC rating the thermal, solar and optical characteristics of complete windows. Like NFRC is based on simulation softwares of the U-factor and SHGC measurements. The annual energy rating of this system is in terms of whether a window is characterized as net energy gainer or looser during a year.
Australia Window Council (AWC), developed a system called Window Energy Rating Scheme (WERS), which rates and labels the energy performance of windows the same way as NFRC and CRS. Manufacturers to participate in WERS must obtain energy certificates of their products first, originally from an organization appointed by the Australia Window Council. WERS certifies the thermal transmittance, SHGC and optical transmittance by rating products in a scale of 1-5 star with 5 representing better heating and cooling performance.
The European Window Energy Rating System(EWERS) with the accompanied label system being already adopted by the British Fenestration Rating Council(BFRC), intends to help interested parties to choose the most suitable energy efficient window among a wide range. This system takes into account the U-value, the solar factor and the ventilation losses, providing each window with a label that indicates its energy performance on a letter scale from A-G, with G representing the least energy efficient. This rating system comes in accordance with the European Directive(2002/91/C) about the energy performance of buildings, which calls for special certificates to be available when buildings are constructed, sold or rented.
All rating systems described above have one common goal, to classify products depending on their energy performance based either on the selected window properties (U-factor-SHGC) or the calculated annual energy balance (heating/cooling loads)[3].

1.3. LABELING WINDOWS

There are various labeling systems worldwide that intend to provide consumers with all necessary information about the energy performance of a product and try to promote the use of such energy efficient products. Obtaining such a label is not mandatory, but manufacturers that achieve a certain lower level are eligible to use the logo and to be listed on the energy saving recommended database.
The label on products allows the classification and the comparison between all rated products, and can be divided to three main categories: comparative, endorsement and informative. Almost all the existing energy rating systems for windows provide such labeling and enable the comparison based on energy consumption, specified properties or both. The English and Australian rating systems are based on the annual energy performance while the American rates only properties. Figure 1.1 below corresponds to the English, Australian and American comparative labels respectively.

Comparative labels are more detailed compared to endorsement which certifies that the product meets certain pre-specified criteria. Endorsement labels assigned for windows are given in Figure 1.2 below, for the European Union, the UK and the USA respectively [3].

(a) (b) (c)

Figure 1.1 Comparative labels

(a) (b) (c)

Figure 1.2 Endorsement labels

1.4. ORGANIZATION

In this study the interest is focused on the environmental performance of window frame materials, namely aluminum, PVC, wood, wood-metal and the double-glazing unit that consist a complete window. A Life Cycle Assessment approach has been adopted to evaluate these window-types regarding their production and assembly, taking into account the associated environmental impacts.

More analytically, chapter 2 is a literature of review on previous life-cycle assessments, mainly related to windows. This chapter presents some of the most reliable studies of the past regarding LCA and demonstrates the correlation to the existing study.

In the third chapter the LCA methodology is extensively analyzed and the assessment steps are presented. Chapter four sets the scope and objective of this study, clarifying functional unit, assumptions and boundaries regarding this analysis. A small presentation of the software SimaPro and the database that has been used is given in the last section of this chapter.

In chapters five and six, the LCA method is applied on the most commonly used window frames (aluminum, PVC, wood and wood-metal), accompanied by the life cycle assessment of double-glazed panes in order to evaluate their environmental performance. This chapter explains the inventory that was considered and the impacts that have been assessed, identifying the cradle to gate emissions and waste heat.

Finally, in chapter seven the most important conclusions arisen from the whole analysis are presented and the key results are explained by recognizing the main differences between the products.

2. Literature of review

In this chapter the most important remarks gathered to end up with an overall view of the latest and most important research studies so far. Each case and approach effort of each study, are presented in order to achieve a better state of the art review and compare it to the present study.

Most published studies so far regarding the life cycle assessment of windows have focused on the impact of the composed materials during the various stages, using as indicators raw materials, energy use- consumption, emissions and costs. The main target of each of the previous research studies, after scope and boundaries set, is the identification of a common functional unit, upon which a comparison of the several window types in the various assessment stages can take place.

It should be noted that all previous LCAs in this review used published data and assumptions have been made, such as the life duration of various windows, which may lead to conclusion variation from one study to the other. Also due to specific boundary conditions set to each study, the verification of the presented results is a complicated task and thus the boundary and assumptions on allocation should be fully known [4].

2.1. LCA DEFINITION

In order to understand the documentation presented in the following paragraphs, we need to be familiar with the scope and definition of life cycle assessment.

Life cycle assessment is a useful technique been used as a tool to investigate and estimate all related environmental impacts of a product or service process from cradle to grave.

It is a methodology to account all raw materials and energy flows "in" and "out" during the various stages of the product's life cycle. These consumed and emitted flows (raw material and energy use- consumption, emissions to air, water and soil) are then in total balance to a given functional unit, and interpreted in terms of impact categories on natural ecosystems.

The methodology is now recognized as the best approach for assessing the environmental performance of a product, and the only method guarantying transparency, objectivity and exhaustivity. On the other hand some comments on LCA address its complexity, the difficulty to get usable results, and the risk of biased use of parts of it [5].

An analytical description of LCA and the several stages will be given in following chapter.

Figure 2.1 shows the life cycle analysis of a product and the various flow inputs and outputs in general [6].

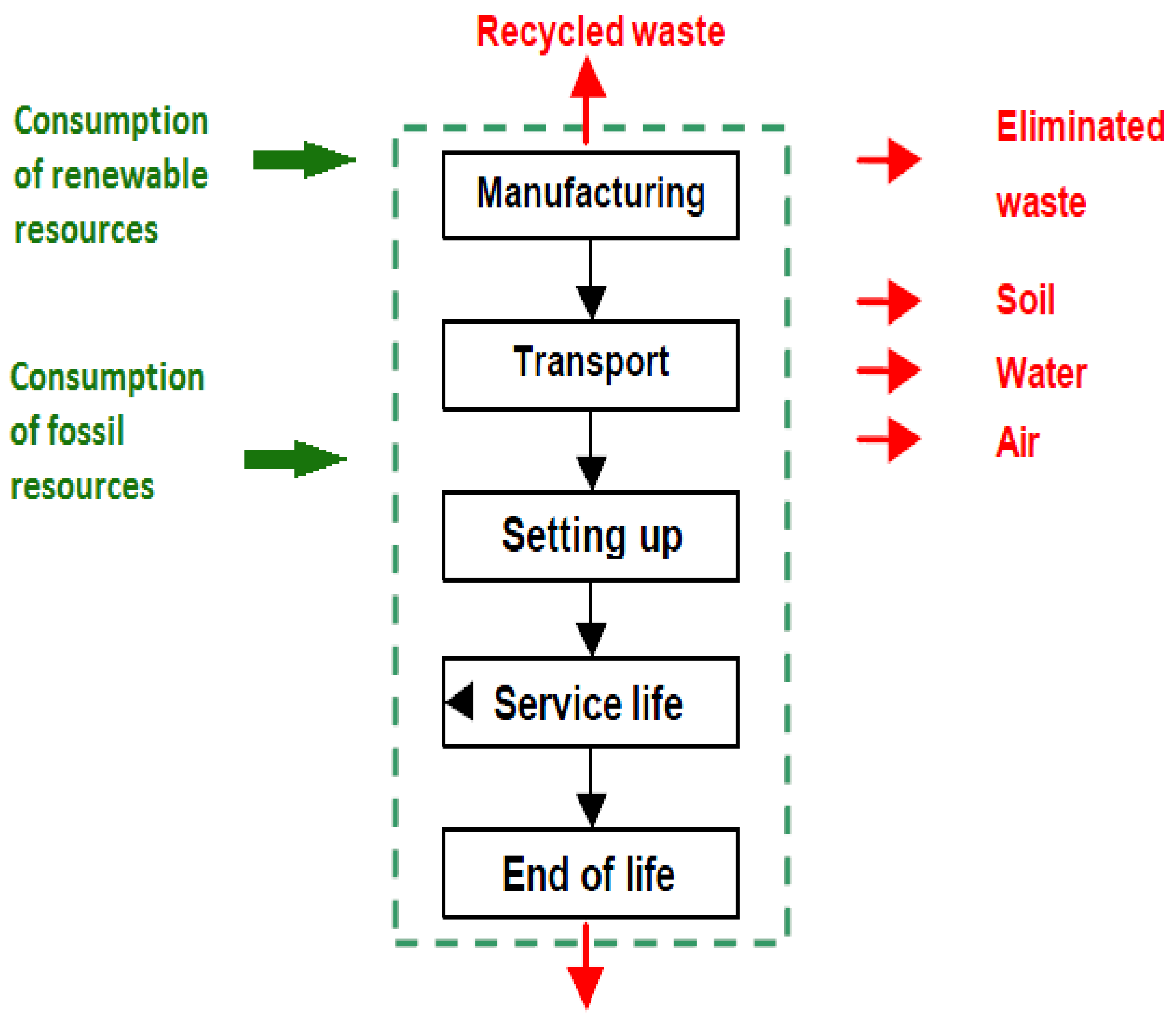


Figure 2.1. Life cycle analysis of a product

2.2. FRAME MATERIALS BRIEF DESCRIPTION

A brief description of the most commonly used materials composing a window, mainly frames materials, is considered vital to form a first picture of the materials involved during the manufacturing stage.

The variety of those materials and the different combinations among them which targets to windows with different properties and for different application cases, leads to different emitted flows (energy intensity, emissions). Different processes (frame production, painting, ironware production) take place depending on the materials used and the desired characteristics of the final window (thermal, solar, visual etc).

Windows perform multiple functions in the buildings envelope and accounts for 10-25% of the total exposed surface. Depending on the climatic data and the latitude of the building under consideration, a specific combination of the desired characteristics will provide the most suitable and environmentally friendly window type selection [2].

As windows are one of the most important building's elements, are required to fulfill a series of functions such as [7,2]:

- Thermal insulation
- Light transmittance
- Air circulation
- Outdoor optical view
- Safety/security
- Protection of indoor environment(pollutant, bad weather conditions etc)

To fulfill all of the above and depending on the location under consideration, many different material families, are involved to meet the requirements in various combinations.

Glass(single, double or triple) depending on the number of panes, coating such as low-e(metal and oxides) for improving the thermal insulation and the lighting entrance, inert gasses(argon, krypton, xenon) for better thermal properties, rubber for the sealant, frames(aluminum, timber, PVC, fiberglass, wood composites etc) of the most important element of the window, are some of the most well known materials and the combination of them is the result of several successive elements assembling phases, some of them strongly industrialized and some not [9].

2.2.1. FRAME MATERIALS

ALUMINUM

Aluminum production[9] is one of the most energy intensive process(225MJ/kg) in comparison with the other frame materials(wood, PVC) and during its process huge amounts of dangerous pollutants are emitted to the environment like, carbon dioxide (CO_2), polyaromatic hydrocarbons(PAH_s), acidic sulfur dioxide(SO_2) and dust. It is the third most abundant metal in nature and the chief ore is bauxite.

Theoretically it is 100% recyclable without any losses on its properties and the energy needed for recycling is about 5-7% of the energy used for primary aluminum production from its ore.

Aluminum windows are characterized by the light weight and durability through time. The cost in general is low and the maintenance needed is almost zero, thus it is an affordable window type, cost attractive, with many property possibilities depending on window composition.

However aluminum windows are highly thermal conductive and in order to improve the insulation capability of the windows, a thermal break made usually from plastic is incorporated into the frame to reduce the direct conductivity between the inside and outside parts of the windows.

PVC

Polyvinyl chloride [9], commonly abbreviated as PVC, consists of chlorine, carbon and hydrogen and is the third-most widely produced plastic. It is a synthetic material and is derived in the biggest part from fossil fuels like natural gas and petroleum.

During the production it consumes big amounts of energy (70MJ/kg) but is not as energy intensive process as aluminum's.

The biggest drawback of this material is the poisonous pollutants such as vinyl chloride, hydrocarbons, heavy metals and dioxins during the production phase.PVC also decomposes really slow and as a waist contains environmentally dangerous substances. The recycling process during the life-end of a PVC product is a complex procedure due to the presence of additives and several reinforced materials.

PVC windows have wide range properties, depending on the additives on the final product. Additives can be plasticizers for improving the processing and reduce brittleness or stabilizers to protect against heat, oxidation and ultraviolet radiation (solar radiation) causing the degradation of the window.

The overall thermal conductivity of PVC windows is low and when metal reinforcements are used to increase the rigidity of the frame, may end up increasing the overall conductivity.

Generally PVC is suffering from high temperatures and ultraviolet radiation which may break the molecular bonds and as a matter of that can cause the embrittlement and discoloration of the product.

TIMBER

Timber[9] is the least crafted material between others and the easiest to process. Lumber (also known as timber) is wood in any of its stages from felling to readiness for use as structural material for construction.
It mainly consists from lignin and cellulose and its composition differs depending on the type of the tree. From tree to tree organic substances such as proteins, sugar resin and water differs giving small scale differences on the final lumber.
The felling of trees, either softwood or hardwood, have many effects on the environment. Thus the environmental concern nowadays is high, with the introduction of sustainable forest management.
For every tree that is felled, another two at least are planted. Having that in mind we are referring to a slow but kind of renewable cycle, defining timber as a renewable material.
The embodied energy of timber is relatively small (5.5MJ/kg), using less primary energy than the market alternatives, PVC and aluminum.
Is the oldest window frame material in use, nominating as the most traditional among others.
Timber as a material possesses good thermal and sound insulation, it is easily processed and formatted for various applications doesn't corrode and given the right treatment doesn't rot.
On the other hand, timber woods have to be painted and maintained every few years otherwise weather conditions and moisture will deface them in a short life-period.

ALUMINUM CLAD TIMBER

Timber frames with aluminum cladding[9] is a way of improving the window properties, by mixing and thus gaining the advantages of more than one material. Cladding with aluminum the exterior face of the frame, aims to protect the timber underneath and raise window properties, ending with a more effective product in terms of durability.
This way the frame is protected against corrosive attacks, maximizing the life-time of the window and minimizes the maintenance of the timber by retaining the attractive wood finish on the interior.

FIBERGLASS

Fiberglass frames [10], offer an exciting alternative to metal, plastic, or wood frame windows. It is proven as superior building material, known for its strength, durability and performance.

Fiberglass frames are essentially glass fibers and risen, saturated together in a heated die. This obtained material is getting more and more popular in windows industry offering a variety of desired characteristics in the final product. Low thermal conductivity (good insulator), high strength, rot resistant and repaintable, are some of the properties characterizing this material. It is impervious to water, cold, heat, insects, salt air and ultraviolet rays—all the traditional enemies of windows. The drawback is the really high cost compared to aluminum, wood and PVC with an unattractive payback period, independently of the long life of this material.

To summarize with, all frame materials individually are characterized by various properties and the final selection should take into account many aspects such as the usage or application under consideration, the weather conditions and climatic data , the environmental impact and footprint evaluation of the various materials and finally the return on investment.
Table 2.a below summarizes some general properties that characterize each frame material separately [9,10].

Material	Thermal Resistance	Durability	Cost	Recycled content
Wood	**very good**	**variable**	**high**	**low**
PVC	**very good**	**good**	**low**	**very low**
Aluminum	**bad**	**good**	**low**	**very high**
Fiberglass	**very good**	**very good**	**medium**	**medium**

Table 2.a.Frame materials properties.

2.2.2. WINDOW AND GLAZING SYSTEMS

GLAZING

Glazing [10] refers to the transparent element part of the window. Glazing is mounted in the window with the assistance of glazing putty and a frame which supports the glass and holds it in place. Historically, windows were single glazed, with a single pane of glass. Today, there are a number of options for window glazing. Double or triple glazed windows create more insulation,

making the structure more energy efficient by reducing heat loss through the windows. Glass can also be tinted to keep out sunlight, coated in a clear film which increases energy efficiency, or otherwise treated to make windows more efficient.
The most familiar type of glass, used for centuries in windows and drinking vessels, is soda-lime glass, composed of about 75% silica (SiO_2) plus Na_2O, CaO, and several minor additives.
Window and glazing choices should be considered holistically. Once the design team and owner agree on the design problem, window and glazing options can be evaluated. Ultimately, the optimum choice of window and glazing systems will depend on many factors including the building use type, the local climate, utility rates, and building orientation.

TINTS/COATINGS

Several minor additives and colorants are added to the glass during production with the form of a film or coating. Any glass that has been treated with such a film or coating is specified as tinted glass. The purpose of glass tints and coatings is the properties and characteristics targeted according to the needs and preferences of the consumer.
Tinted glass in dwellings serves many practical purposes such as reducing transmission of light(ultraviolet rays), avoid solar heat gains inside the house(reflecting coating) and block or reflect different amounts and types of light.
Coatings [10] , usually in the form of metal oxides, can also be applied to glass during production. Some of these coatings, called "low-emissivity" or "low-e," help reduce radiant heat transfer between panes of glass by blocking some or all of the IR wavelengths. These coatings can dramatically lower the window U-factor.

INFILL GASES

The use of inert gases [11] such as argon, xenon or krypton between panes of glass, reduces conductive and convective heat transfer. By injecting them in the spaces between sealed glazing, the overall U-value of the window is been reduced. This means decreasing thermal losses through the window and thus improves the building's performance and reduces consumer fuel bills. You also put a lesser burden on the environment from atmosphere pollution during the use phase of the window.
The high insulative properties of inert heavy gases are due to the hyperbolic relation between thermal conductivity and molecular weight: as the molecular weight rises, the thermal conductivity drops dramatically.

2.2.3. ANATOMY OF MODERN WINDOW

All the above mentioned parts (frames, glazing, coatings, infilled gases, etc) have a specific role to the final window product, giving different characteristics depending on the consumer's preferences for the various utility functions.

A modern standard window for most cases is being presented in Figure 2.2[8] to demonstrate the anatomy of a common window and the location of the parts composing it.

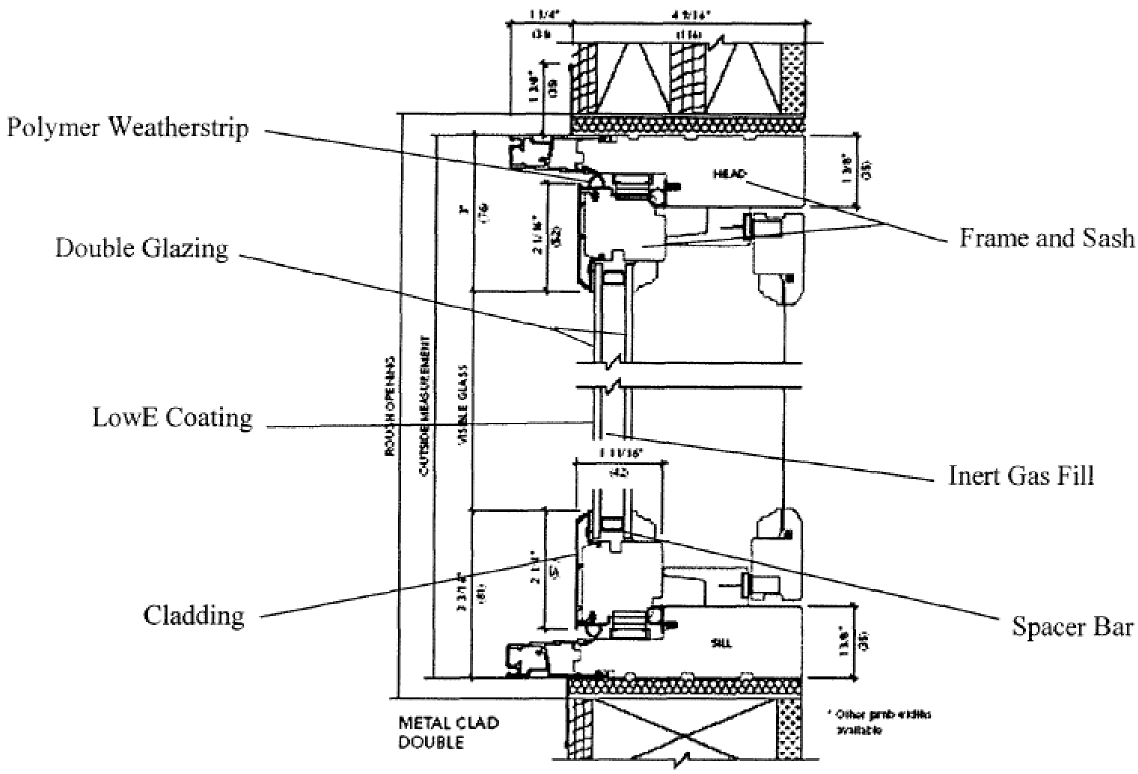


Figure 2.2. Typical modern window

To add with, Polymer Weatherstrip (flexible polymers) is used to create a weather proof seal between the fixed frame and operable sash, while spacer bars are used to separate multiple glazings. Aluminum and foam spacer bars are most commonly used, with foam providing better thermal break between surfaces.

Lastly, cladding (aluminum, PVC, fiberglass) is applied to protect traditional wooden frames from decay and extra maintaining costs in time, keeping window properties inalterable as long as possible.

2.3. STATE OF THE ART

Most of the few available studies published so far regarding life-cycle assessments of windows, have generally targeted on two purposes [6]:

1. The comparison between frame materials, defining the methods used during the life-cycle of the material individually and finally the relative contribution to the various environmental impacts.

2. The justification of energy and resource use during manufacturing, estimated emissions and the implementation of new technologies for improved use-phase characteristics.

To approach the different nature of these two goals, different design of LCA's on windows applied reflecting the diversity of the scope analysis.
For the first purpose, the focus is directed on the methods or processes that are related to the frame material. These processes are in direct comparison from one frame material to the other and refer to cradle to gate emissions and resource use, secondary manufacturing stage, maintenance, service life and rate of recyclability.
The second purpose refers to the use-phase and the energy payback during this phase. The comparison in this case takes place between carbon emissions or energy use after considering the life-cycle inventory and the expected energy savings during use or generation during use.
Some LCA studies approach both issues in the same case comparing stages of life-cycle, methods or processes and energy savings.

Weir and Muneer(1998) were the first to publish LCA of an inert gas filled, double-glazed window. The study considered mainly 2 frame materials, timber, aluminum, glass panes and 3 inert fill gasses, argon, xenon and krypton. Moreover sealed glass unit production as well as heat and lighting during manufacturing stages were other aspects of this study [4].
The major source of data for this analysis is the result of a detailed audit of manufacturing processes, undertaken by the authors, at the window production plant of Nor-Dan Windows, based in Moi, Norway.
Energy expenditures, embodied energy of raw materials and greenhouse gas emissions were estimated during each step of the analysis and for each manufacturing process separately.
The introduction of a reference window with specific dimensions allows the comparison among the obtained data and enables finally to draw conclusions [11].

The embodied energy estimation for the timber sash and frame, inclusive of timber processes and laminated glue is 195.3MJ in given dimensions (1.2mx1.2m) and a glazing area of 1.1m^2, while for the aluminum and the same reference window is 517.5MJ assuming 100% primary aluminum or 408.8MJ with the assumption of 27% use of recycled aluminum.
For the inert fill gases xenon was the most energy intensive while argon the least. The embodied energy for argon, krypton and xenon was found to be 1031MJ, 1539MJ and 5531MJ respectively, yielded 94.7 kg of CO_2 for argon, 207.6 kg for krypton, and 1,094.7 kg for xenon for the same reference window.
Finally for a chosen window of dimensions 1.2 m by 1.2 m, the energy requirement for manufacturing process was 33.2MJ for sash and frame, 6MJ for glass sealed unit, 0.2MJ for aluminum process and 99.7MJ for lighting and factory services, yielding to a total of 137.1MJ.
Tables 2.b and 2.c below present summarized results of this study regarding energy content of the aggregate processes and the energy content of the five elements considered [11].

Table 2.b Summary of energy content for manufacturing processes

Function	Energy requirement per window (MJ)
Timber sash and frame	33.2
Sealed glass unit	6.0
Aluminium processing	0.2
Lighting and factory services	97.7
Total	137.1

Table 2.c Summary of energy content for raw materials and manufacturing processes

	Embodied energy (MJ)		
Window component/function	Argon	Krypton	Xenon
Inert infill gas	0.01	508.2	4500
Timber	195.3	195.3	195.3
Aluminium	408.8	408.8	408.8
Glass	289.4	289.4	289.4
Manufacture	137.0	137.0	137.0
Total	1030.51	1538.7	5530.5

Entec (2000) considered LCA on wood and PVC frame materials for windows, starting with a comparison of primary production from raw materials up to the decomposition, final disposal and landfill at the end of use. Processes like frame fabrication and installation were also contained in this study as well as thermal effects during the use phase of the window.
The final results through a direct comparison between wood and PVC production stage of raw materials showed that PVC window consumed 3 times as much coal and oil as the wood window and in an extended analysis produced 7 times as much CO_2. Moreover, wood window due to tree growth acted as carbon sink with 32.3 kg of $C0_2$ to be consumed as part of that and 7.5 kg to be released back during the end of life [12].

Citherlet et al. (2000) provided an LCA approach to an economic estimation and environmental impact of advanced glazing systems. A cradle to grave evaluation took place after the separation of the glazing systems into their main components. Number and types of panes, infilled gases, spacers and frame materials summarize the analyzed components on which a complete LCA was computed individually with the assumption that the window lifetime corresponds to the longest element lifetime.
The analysis starts with the extraction and production of basic materials, continues with the production of the main components of windows with a percentage of breakage and loss on this phase, to the assembly and maintenance of the window, ending up with the final destination (recycling).Figure 2.3 below contains all processes during the whole lifetime of the glazing systems as studied in this analysis.
During all phases considerable non-renewable energy consumption as well as production of polluting emissions were further analyzed, after dividing them in indicators such as gases(CO_2) responsible for global warming, gases responsible for acidification(SO_x) and photochemical ozone production(C_2H_4).
To end up with, the windows were tested to compute thermal balance and energy costs-savings during use phase with Lesosai4 software. A functional reference room was simulated for different climates (Glasgow, Lausanne, Rome), different orientation and different glazing systems. The results illustrate that improved thermal insulation rapidly drops energy consumption during the utilization phase of the window and this outweighed increased energy production requirements. That means even if advanced windows have a higher environmental impact than that of a standard window during life-cycle, compared to the potential gains during utilization phase are insignificant [7].

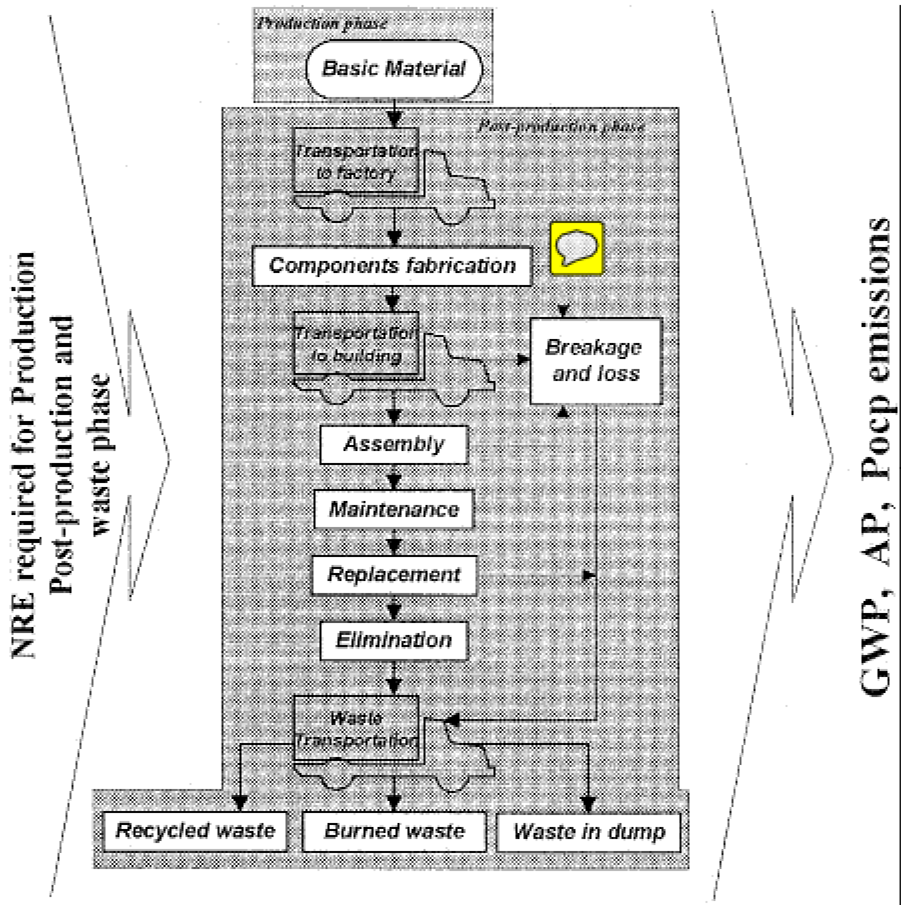


Figure 2.3 LCA method for advanced glazing systems.

Asif et al. (2002) presented a comparative article of materials used for window frames, underlining the embodied energy of the final windows. A life cycle assessment (LCA) was carried out for the four types of frames: aluminum, PVC, timber and AL-clad timber, analyzing the energy consumption and environmental impacts during the production phase.
A reference window with dimensions 1.2mx1.2m was used for the evaluation and the comparison of the embodied energy, which resulted to 6GJ, 2980MJ, 1460MJ and 995 MJ respectively.
Aluminum production (225MJ/kg) was the most energy intensive while wood frames the least (5.2MJ/kg). Moreover aluminum and PVC frames were the biggest burdens for the environment, emitting big amounts of dangerous pollutants while timber frames had the least pollution. Figure 2.4 below presents the embodied energy of the frame materials in a graph as showed in this study.

Finally, this study includes accelerated simulation aging tests, to assess the weather performance of the various frame materials and the durability against time. These tests included immersion, dry-wet cyclic, salt spray, humidity and temperature, and UV exposure.
PVC was found vulnerable against high temperatures and UV radiation with the shortest service life of 24.1 years.
Timber frames showed warping and cracking under extreme humidity and temperature, requiring frequent maintenance and painting to expand the service life which in this study was estimated 39.6 years.
Uncoated aluminum frames get damaged in the absence of protective coatings under corrosive conditions, and the estimated service life is 43.6 years.
Al-clad timber frames, did not receive any deteriorating impacts under any of these conditions due to the well protective coatings and although new to the market, is expected to last more than 45 years.
Table 2.d below summarizes the estimated service life for the various frame types been discussed on this study[9].

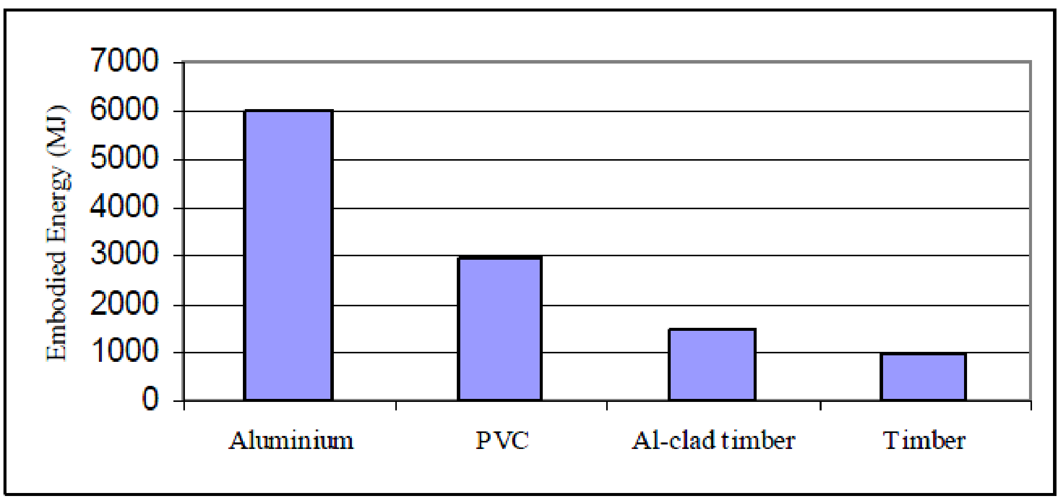


Figure 2.4. Embodied energy of window frames

Window (frame type)	Estimated service life			Characteristics
	Mean	Median	Inter-quartile range	
Aluminium	43.6	40	12.5	Low maintenance
PVC	24.1	22.5	15	Low maintenance, difficult to repair
Timber	39.6	35	16.3	High maintenance, easy to repair
Al-clad Timber	46.7	45	10	Low maintenance, easy to repair

Table 2.d. Survey analysis results

Kiani et al. (2004) involved with the life cycle assessment of glass associated with a building's fully glazed envelope considering energy consumption, the embodied energy of participating products and energy use throughout different stages of the life cycle.

Energy consumption refers to the stages of glass manufacturing, the assembly of the glazed unit, demolition and recycling of the glass, as well as the operational energy use during utilization phase.

As in more of the studies, system boundaries and functional unit were also introduced on this paper to come up with comparable results through simulation with a modeling software.

Two types of glass were analyzed, the first type was tinted glass with the lowest reflectance while the second one was reflective glass with the lowest absorbance.

Results showed that in a life-period of 25 years, the embodied energy related to manufacturing, assembling and transportation can be counted to 21.1%. Furthermore, the operational energy use of a fully glazed building can be reduced up to 53% by using less transmittance glass and high performance glazed units, which far outweighed the increased manufacturing energy, a savings of 12283 GJ against an increase of 1536 GJ in a period of 25 years. Other results shown indicate that recycling of glass has to be carefully planned otherwise there might be just 2.5% saving energy by recycling of glass as cullet.

Figure 2.5 below compares the embodied energy during the stages of manufacturing, assembling and transportation, in relation to the energy during operational phase.

The difference in operational energy(12283GJ) can be gained with the cost of the difference in energy consumption(1536GJ) from cradle to grave, by improving thermal characteristics of the window[13].

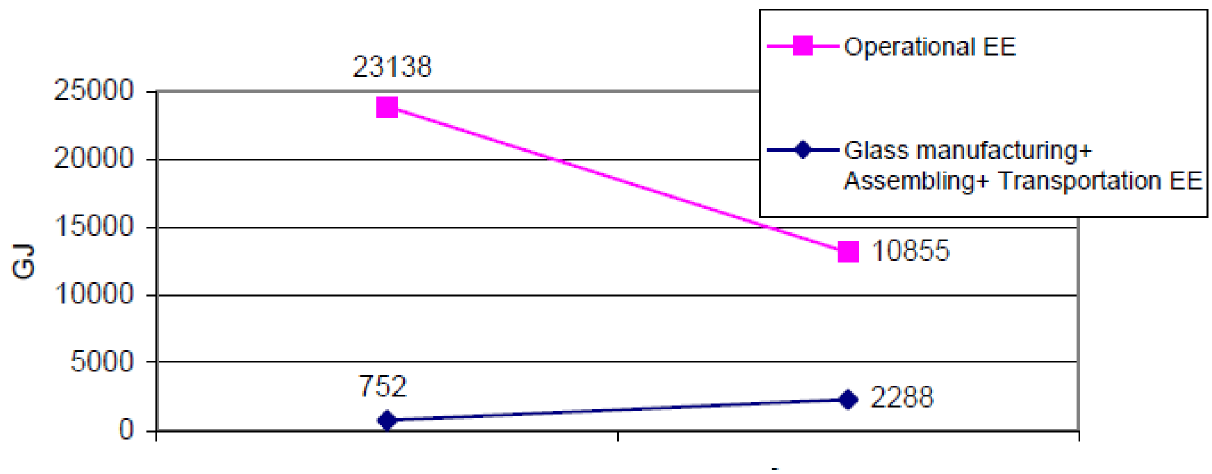


Figure 2.5. *Life cycle embodied energy of glass over a 25-year operational period*

Recio et al. (2005) evaluated the environmental impact, performing LCA mainly in 3 frame materials: aluminum, wood and PVC. The life cycle assessment evaluated environmental impact in terms of embodied energy in production as well as CO_2 emissions during manufacturing, use, recycling and final disposal of waste materials.

The analysis took place after boundaries and functional units were set, with the casement reference window dimensions of 1.34mx1.34m in a standard room in Spain.

Both options of single or doubled glazing were analyzed and particularly in aluminum case the option of thermal break was also included.

The first results obtained from the analysis, refer to energy consumption and $C0_2$ emission during the stages of extraction and production of the main materials.

The embodied energy of the wood frame with the single glazing was found to be 44.7kWh corresponding to the lowest energy consumption, while double glazing aluminum had the highest with 1981kWh if no recycled materials included, or 1407kWh with 30% recycled aluminum. Moreover, PVC energy consumption during same stages was found to be 214kWh if 30% recycled PVC included and 254kWh if not. Table 2.e below summarizes energy consumption and CO_2 emission during extraction and production stages.

Although the wood window was shown to have the lowest embodied energy in comparison with the 3 materials considered, the assumption of higher conductivity coefficient of PVC frame outweighed the benefits in the manufacturing stages.

The results obtained from the analysis, indicate that the highest percentage (42%-97%) of energy consumption for all types of windows corresponds to the utilization phase of the window. The extraction and production stages account up to 52%, 14%, 4% for aluminum, PV and wood respectively.

Finally, the main conclusion of the overall energy consumption contain all stages of the life-cycle of the window and is been presented in Table 2.f.

The PVC window with 30% recycled materials consumed overall the least energy(1740kWh), emitted the least CO_2(730kg) and consists of 49.2kg (93,4% of the total) of recycled materials considering all stages from cradle to grave.
The wooden window with double glazing presents energy consumption of 2045kWh and CO_2 emissions of 886kg while the recycled materials accounts for 61.5% of the total.
Aluminum window was found to have the highest values of energy consumption (3244-4413kWh) with the best case scenario referring to 30% of recycled materials and the use of thermal break, while the worst case refers to the absence of thermal break and the use of 100% primary aluminum. The emitted CO_2 is ranging from 1418kg for the best case to 1935kg for the worst respectively. In all cases aluminum windows provided 62.2kg of recycled materials counting for 94.1% of the total [2].

	Energy consumption		CO_2 emission	
	kWh	%	kg	%
Wooden window, single glazing	44.7	1.7	13.7	1.2
Wooden window, double glazing	74.5	3.6	22.2	2.5
PVC window, 30% recycled PVC	214.0	12.3	66.3	9.1
PVC window, 0% recycled PVC	253.6	14.2	77.6	10.5
Aluminium window, no break, 30% recycled Al	1,406.5	36.6	613.5	36.5
Aluminium window, with break, 30% recycled Al	1,406.5	43.4	613.5	43.3
Aluminium window, no break, 0% recycled Al	1,981.1	44.9	867.9	44.8
Aluminium window, with break, 0% recycled Al	1,981.1	51.9	867.9	51.9

Table 2.e. Embodied energy and CO_2 emission during extraction-production stages

Window	Electrical consumption (kWh)	CO_2 emissions (kg)	Recycled material (kg)					
			Glass	PVC	Steel	Aluminium	Total material recycled	% of total material
30% recycled PVC with double glazing	1,740	730	21.4	21.1	6.7		49.2	93.4%
0% recycled PVC with double glazing	1,780	742	21.4	21.1	6.7		49.2	93.4%
Wooden with double glazing	2,045	886	21.4				21.4	61.5%
Wooden with single glazing	2,633	1,155	10.7				10.7	45.0%
30% recycled aluminium *with break* and double glazing	3,244	1,418	21.4			40.8	62.2	94.1%
0% recycled aluminium *with break* and double glazing	3,819	1,672	21.4			40.8	62.2	94.1%
30% recycled aluminium *without break* and double glazing	3,838	1,681	21.4			40.8	62.2	94.1%
0% recycled aluminium *without break* and double glazing	4,413	1,935	21.4			40.8	62.2	94.1%

Table 2.f. Overall energy consumption and CO_2 emission during all life-cycle stages.

Syrrakou et al.(2004) was the first to study life cycle analysis and the related environmental impacts concerning an electrochromic glazing device (ECD) that uses low voltage to range the transmittance properties of a window[14].
As it is not commercialized yet, this study analyzes embodied energy as well as energy savings of this technology in comparison to a typical widely-used insulated glass unit (IGU).
The basic materials composing an electrochromic device (K-Glass, PC and PMMA) and the production processes that correspond to those materials, are analyzed in detail and account for 98% of the total device mass.
The results indicated that the total embodied energy was 49MJ/ECD while CO_2 emitted during the production processes was 810g. K-Glass represents 66% of the total mass or 32MJ/ECD of the total energy consumed during production stage with 310g of CO_2 emission.
The most energy demanding process was proved to be that of the PMMA (101 MJ/kg) while LiCLO4, PC and K-Glass follow with 85.5, 47.7 and10.7 MJ/kg of product, respectively.
A reference unit glaze (40cmx40cm) was set to allow the comparison of the embodied energy between an ECD and various IGUs. The final comparison took into account a complete electrochromic window case with frame against an argon filled IGU, and resulted in same energy requirements to be produced, 431-471MJ/unit compared to 431MJ/unit respectively.
Taking into account their improved overall performance (thermal and optical) as well as cost similarities to that of the best available IGUs, the energy savings during the use phase of electrchromic glazing would certainly prevail.
Figure 2.6 corresponds on the composing materials and their participation on the total embodied energy regarding ECD production.

Material	**MJ/ECD**
K-Glass	32.13
WO_3	-
PMMA	2.31
Propylene Carbonate	12.00
Lithium Perchlorate	2.18
Silicone	0.37
Total	**48.98**

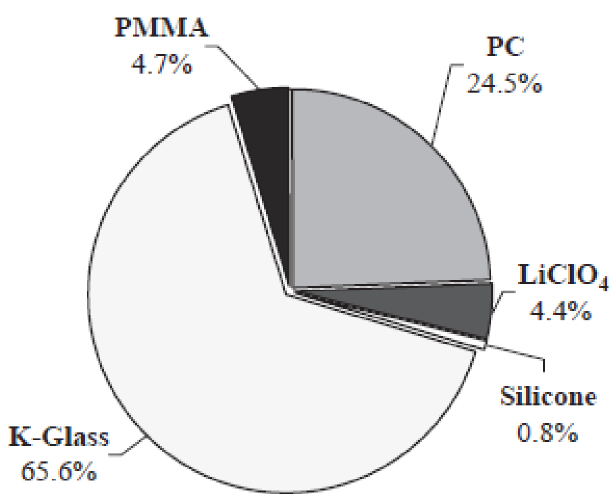


Figure 2.6. Contribution of materials in ECD embodied energy

Papaefthimiou et al. (2005) provided a life cycle assessment on a prototype electrochromic window not widely used yet, to evaluate its energy efficiency. The main consideration of this study is the energy consumption as well as the energy savings during the use phase of such advanced system, simulated for various scenarios of representative cases of use in Greece. The analysis took place on a 40cmx40cm electrochromic case device, mounted on a 50x50cm aluminum frame, coated with a tungsten oxide film (WO_3), routinely fabricated in the laboratory. Such a device uses a low voltage film altering the light transmission characteristics of the window.

For the production phase of the EC window, the energy use was 2261MJ, of which 91%(2042MJ) corresponds to aluminum frame production, about 7%(166MJ) to fabrication processes and the rest 2%(53MJ) to the embodied energy of raw materials.

According to this analysis, the use of EC window instead of a single glass with a maximum expected lifetime of 25 years would reduce energy up to 54%, yielding to energy savings of 6388MJ. Finally in financial terms, the total energy cost savings varies from 228-569 euro/m^2 for 10 or 25 years of EC window operation respectively.

Figure 2.7 below refers to the energy use and savings during the various stages of this analysis [3,15].

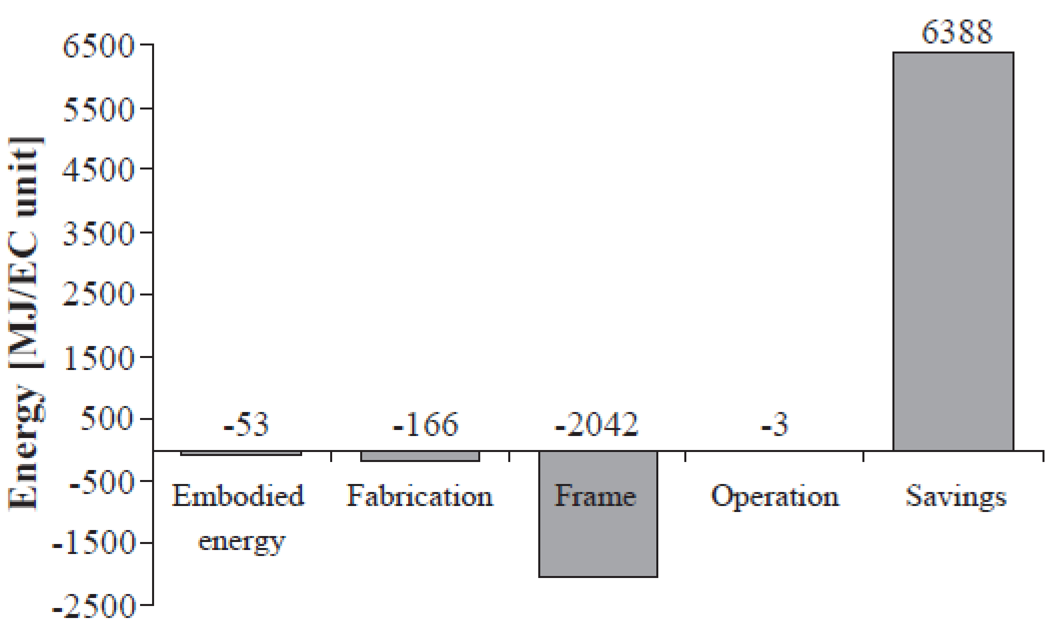


Figure 2.7. Energy analysis of electochromic prototype

Salazar and Sowlati (2008) considered the most recent life cycle analysis regarding window frames commonly available to North America, taking into account three main materials, PVC, fiberglass and wood covered with aluminum cladding.
All three window types were represented by a single manufacturer with standard options such as reference dimensions (600mmx1200mm), double-glazing, low e-glass, standard frame depth and operable function.
The LCA study included all life stages from raw material extraction and commodity manufacturing to product manufacturing, installation, maintenance and disposal at the end of life while transportation of the materials was considered up to the point of installation.
The scope of the analysis was to estimate and evaluate the environmental impacts as well as the human damage that were pre-defined and grouped into four main categories, most relevant to the ultimate damage caused by the three life-cycles: respiratory inorganics, terrestrial acidification/nitrification, global warming, and non-renewable energy.
The fiberglass and aluminum-clad wood windows used the least non-renewable energy during their life cycles, caused them to be superior in the four categories. The primary contributor to greenhouse gasses in the three life cycles was the cradle to gate commodity manufacture and secondary manufacturing energy.
The cradle to gate manufacturing of the three windows required similar levels of non-renewable energy. This indicates that the fundamental differences between the damage associated with the use of the three windows lies with the service life that is assumed. The cradle to gate analysis showed that the wood and PVC materials alone, actually use less non-renewable energy than fiberglass, but the requirement for cladding and steel reinforcement caused the total frame impacts to be greater.
Finally, the sensitivity analysis revealed that while several categories were significantly affected by the selection of data sources, the four non-renewable energy related categories were unaffected with an exception to assumptions regarding carbon sequestration.
After concluding to those results, the author attempts a suggestion of potential improvements such as use of alternative cladding materials, higher participation of recycled materials, reduction of manufacturing energy with more efficient heating and lighting energy sources or more efficient processes, and last the extend of the service life of installed windows which reduces the need of replacement[4,8].

Tarantini et al. (2011) used life cycle analysis to identify the environmental impacts of wooden windows and the critical processes that take place on the various life-cycle stages.
The LCA case study was conducted by ENEA and the aim of this analysis was to develop a structured approach for GPP (Green Public Procurement) and define the criteria needed to support it.
A reference window composed from the most common materials (wood species, preservatives, glue, paints and ironware) was developed, manufactured in Italy and mounted on a residential building in Bologna to be evaluated.
To select the most used technologies and materials a survey has been conducted within roughly 1000 enterprises and consultations with manufacturers associations.
SimaPro 4 was the software used as the modeling program and contains several internationally accepted methodologies within it to evaluate inflows and outflows, as well as the environmental impacts in various categories, such as primary energy consumption and solid waste production.
The results pointed once more, the high contribution of the use-phase of the window to the green house effect in comparison with the other phases of production, maintenance and end-of-life. Moreover the contribution of the most relevant processes of the window production phase were analyzed, to conclude that the double glazing production is the most emitted process contributor to greenhouse effect, followed by the production of the semi-finished wood tables used for the assembly of the window frame.
Figure 2.8 corresponds to the contribution of the wood life-cycle to the green house effect, while Figure 2.9 corresponds to the participating processes during production phase to greenhouse effect [16].

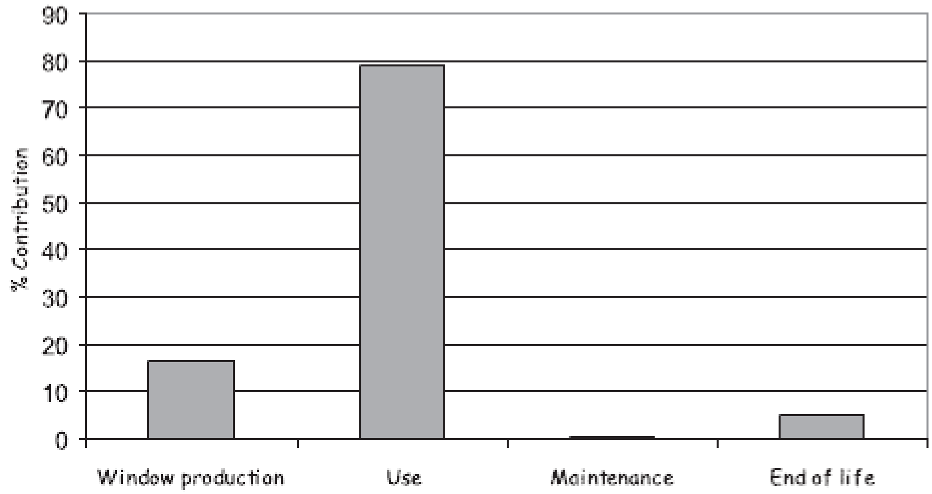


Figure 2.8.Contribution of wood life-cycle to green house effect

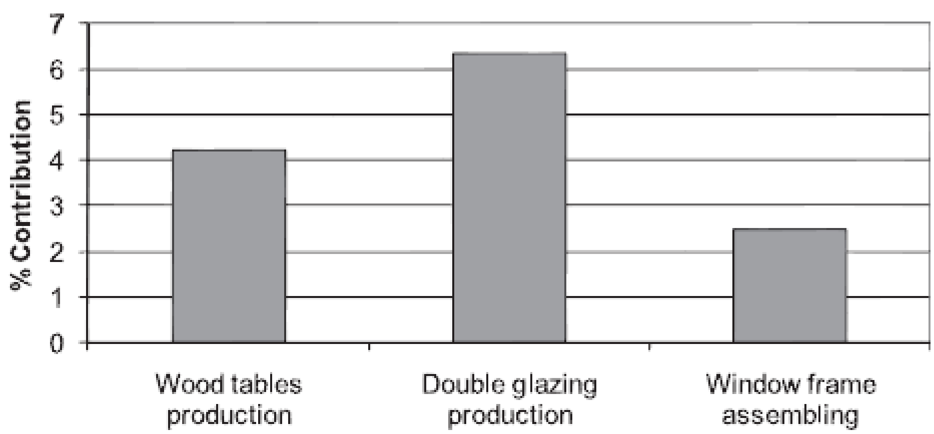


Figure 2.9. Contribution of production processes to green house effect

Table 2.g below summarizes all LCA studies presented on this chapter in chronological order to gather all previous efforts and the most important remarks regarding window systems. Goal and functional unit are defined for each study separately to sum up into a quick overall view of the existing research on this sector so far.

Study	Goal	Functional Unit
Weir & Muneer 1998	Consider relative impacts	Double glazed wood window
Entec 2000	Compare frame materials	Wood & PVC window frames
Citherlet et al. 2000	Compare frame materials & justify energy payback	Numerous window systems
Asif et al. 2002	Compare frame materials	Aluminum, PVC,timber & Al-clad timber frames
Kiani et al.2004	Justify energy payback	Fully glazed building's envelope
Recio et al.2005	Compare frame materials & justify energy payback	Aluminum, PVC & wood frames-single or double glazed
Syrrakou et al.2005	Justify energy payback	Electrochromic window
Papaefthimiou et al.2005	Justify energy payback	Electrochromic window
Salazar & Sowlati 2008	Compare frame materials	Windows & frame systems
Tarantini et al.2011	Compare frame materials	Wood windows

Table 2.g. Summary of previous LCA studies on window systems

3. Life cycle assessment method

This chapter describes the method of life cycle assessment and analyzes all stages that participate in the evaluation of a product or service associated with the environmental burdens from “cradle to grave”. All phases over the lifetime of a product are examined separately from the extraction of raw materials to the final treatment and disposal of the product.
During these stages, inflows and outflows in the form of materials, energy and emissions are considered individually for each LCA step. This way the more critical environmental activities over a product’s lifetime are easily detected.
Moreover, LCA is a framework for imposing more strict energy policies through more efficient technologies and processes, resulting to more “green” products and services.

The main phases of LCA are:

- Raw materials extraction/ Resource processing
- Production processing/ Manufacturing
- Installation
- Use
- Maintenance
- Final disposal
- Recycling
- Waste management
- Transportation on each previous phase

Each above mentioned phase is characterized by distinguished flows (in and out) and should be analyzed separately to evaluate the partial contribution of each one of them to the final resulted data. This way a more understanding assessment of the most critical phases over the life-cycle with the most critical processes that participated is achieved to finally end up with all necessary actions that should be considered for further improvement.
In most cases regarding window systems, the most environmental troublesome phase has proved to be the use phase as it has to do with the energy savings over the life-time of the window and the nature of the energy mix that is consumed.

Figure 3.1 illustrates a generic product life-cycle and shows its related product system, which includes the product and all flows of materials and energy use for each life stage. Each arrow represents transportation of materials between each life stage and is necessarily included in the lifecycle and product system definitions [8].

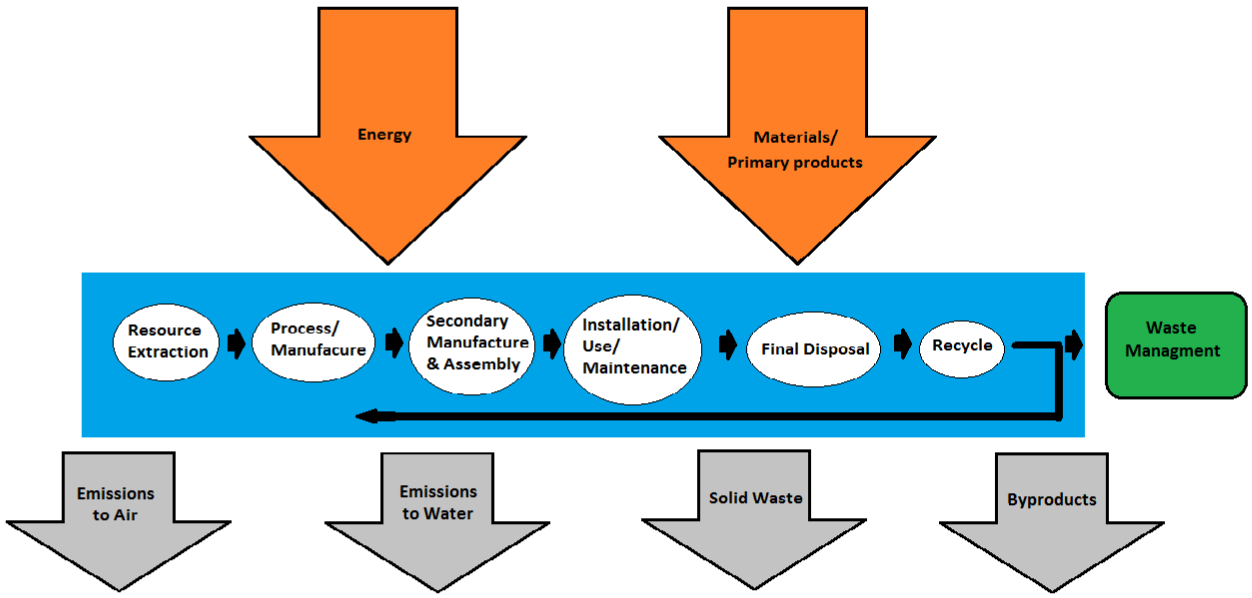


Figure 3.1. Product life cycle flow representation

Life cycle assessment is a technique based on the assumption that products and processes have life cycles with different stages. Various methodologies were born on early 70s to calculate energy flows and materials, often with the absence of environmental impacts to predict future supplies associated with economic values and costs.

Until the late 80s and early 90s, LCA consisted primarily of emissions estimates and was typically used internally to evaluate packaging alternatives like in case of coca-cola. As the oil crisis diminishes on late 80s, the concern over hazardous wastes begun to rise while the life cycle thinking started to take a different shape in Europe. The desire to move from emissions to impact estimates and environmental concerns led to the introduction of life cycle impact assessment which converted emissions to actual environmental impacts.

On early 90s LCA was used for external purposes such as marketing but the questionable data, the manipulation of results and the lack of transparency under market pressure reduced confidence in LCA and its adoption. The need to standardized LCA approaches and the validity of such emerged and efforts started to establish a methodological framework within the scientific community. The Society for Environmental Toxicology and Chemistry (SETAC) did the first attempt towards standardization with the publication of Code of Practice on 1993, describing the components and methodology of the "traditional" LCA. The main three methodological components are the goal and scope definition, inventory analysis, impact assessment and improvement assessment [17].

The International Organization for Standardization (ISO) is a worldwide federation of national standards bodies which through technical committees, prepares international standards for various topics. After the demand grew for better established standards and with SETAC having set the foundation of LCA, ISO adopted the three main components developing the main principals and framework of LCA with the publication of ISO 14040, "Principals and Framework" on 1997.

The structure of LCA initially includes the aims and scope of the study, the collection of all necessary data such as flows and resource use related to the process or service assessed, the assessment and grouping of the impact categories related to the system and finally the interpretation and evaluation of the results [5]. Figure 3.2 shows the relation of the four LCA components in the order that have been introduced [8].

In the following years ISO published three other standards for further defining LCA, ISO 14041 which covers the part relevant to the life cycle inventory, ISO 14042 for the section of the environmental life cycle impacts and last ISO 14043 for the interpretation and evaluation of the results. In 2006 ISO released an update edition targeting to improve readability and removal of errors and inconsistencies by replacing the previous standards with ISO 14040:2006 and 14044:2006 which are now the consensus of methodology of life cycle assessment LCA)[19-23].

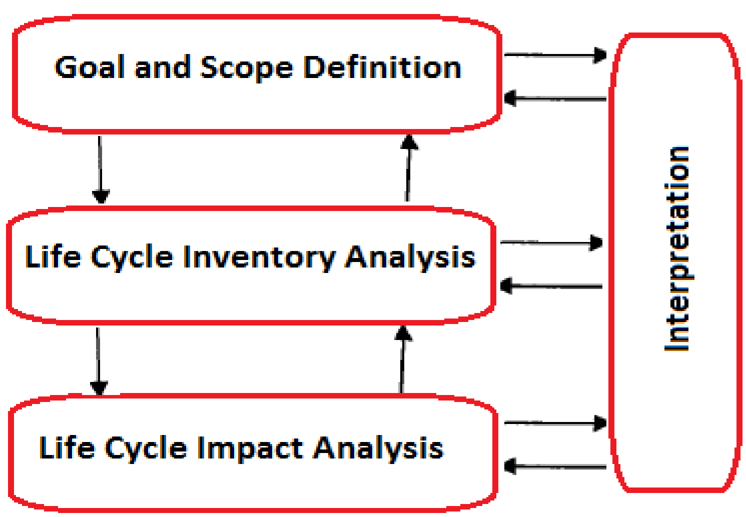


Figure 3.2. Life Cycle Assessment Framework (ISO 14040)

3.1. SCOPE AND GOAL DEFINITION

The first step of life cycle assessment (LCA) is the determination of the goal and scope of the study. In this phase the reasons for conducting the LCA study is defined to specify the system's model and the boundaries of the system while the objective of the study has been set. Furthermore the depth of the analysis, the functional unit, the nature of the data and the validity or quality of the sources, as well as the assumptions or restrictions applied inside the system's boundaries, all should be clarified at the beginning of this phase.

3.1.1. SCOPE

In this step, the product system or process to be studied is identified and the reason for the implementation of the LCA is specified. The scope raises the functions of the system and identifies the boundaries within which the system will be assessed. Moreover this step determines the functional unit upon which all calculations will take place in the analysis, as well as all assumptions limitations, data requirements and type and format of the final report.
The determination of the scope of the study is based on the use of the results. The results can be used for internal exploitation from an institution or an organization, or for external exploitation (e.g. public interest)[5]. Generally, LCA can be used in two main ways:

a) To define the total environmental impact of the product compared to the target set by the production company. A company can be supplied, by an LCA study, with the data needed in order to choose among different production designs applied or different materials used, based on their environmental impact.

b) To define the most significant environmental impacts of a product and how those are caused.

The scope of a study is the leading indicator which points the direction of the LCA study and defines the course of such analysis. Thus it should be carefully examined and define the purpose of it, to conclude on potential results relevant to our cause.

3.1.2. GOAL

In this stage, the expectations and the contribution of the LCA study is being revealed. Goals can refer to a better understanding of the system under study, the estimation and identification of the main environmental impacts and burdens during the life-cycle of a product or process,

the comparison of the estimated results with those of other existing systems, the contribution to develop databases which can help as support tools, and many more. Whatever the case, the goal refers to the way on which a study that has been carried out can contribute to the further knowledge on specific fields, a very important issue in the community of science.
Even though that secondary goal may occur during LCA without being preplanned, the main goal is directly linked to the scope of the study and the expected results.
Main objective of most of the LCA studies is the quantification of environmental impacts during life-cycle stages(from production to disposal) and the use of the findings as necessary data needed for important decision making, that aim to product or process improvement. The primary goal is to choose the best product, process, or service with the least effect on human health and the environment.
The defined goal and scope will guide the entire process to ensure that the most meaningful results are obtained. Every decision made throughout the goal definition and scoping phase impacts either how the study will be conducted, or the relevance of the final results [24].
A list of the most common goals and scopes of LCA studies follows as recognized in LCA101 (Salazar et al):

- **Support broad environmental assessment**
- **Support public policies**
- **Support product certification**
- **Establish baseline information for a product/process**
- **Guide product and process development**
- **Rank the relative contribution of individual steps or processes**
- **Identify data gaps**

3.1.3. FUNCTIONAL UNIT

A product or process under assessment is identified by its functional unit that describes the utility function of the system being studied. This is achieved by the proper organization of the data formally stating the service provided by the product/process, so all flows (raw materials, energy, emission etc) in and out of the providing this service, can be determined. It is necessary to select a proper common functional unit upon which comparison among products and/or processes can take place, leading to accurate results. This ensures that the products/processes that are being compared are true substitutes for each other.

The most common functional unit related to most LCA studies about windows refers to certain dimensions of the window system under study. This way different type of windows characterized by different materials and thus different properties can be compared in terms of a reference window.

3.1.4. SYSTEM BOUNDARIES

An important part before analyzing a system is the formulation of its boundaries based on the scope of the LCA and the initial data collection. This way, all processes and actions within the framework are separated from those outside of the system boundaries. These external processes are not directly linked with the system under study, and belong to the "systems environment" without affecting the system assessed [5].
Defining a system and all processes that connect together different flows in and out of the boundaries, is a quite important issue for better understanding of the studied system and the proper use of the results that are so greatly influenced on the accurate description of the boundaries drawn.
According to UNEP (2005), at least three types of boundaries can be considered in the life-cycle inventory (LCI) analysis. These are the following [17,25]:

- **Boundaries between the system and the environment:** These boundaries differentiate the types of environmental and economic processes that included in the system from those excluded. It is important to carefully select the borders of the system and discriminate the processes in and out the system because they may affect the results of the study.

- **Boundaries between the system under study and other related systems (or allocation):** The third type of boundaries addresses the removal of processes that were included within the system from the LCI analysis. . Processes can be removed (or cut off) for two reasons:

1) For simplicity; some processes that do not represent a large part of the flow or during assessment were found to have insignificant environmental consequences are not analyzed, and
2) Due to lack of data accessibility, a process cannot be quantified due to absence of info and data.

- **Boundaries between relevant and irrelevant processes (or cut-off):** These system boundaries refer to the way that the environmental load is allocated in a “multifunctional process”. A process is called multi-functional process when generates several different products as a result of co-production, recycling or waste processing (e.g. petroleum refining).Emissions and resource extractions of such as process must be allocated over the different functions that this process provides. Whether all products of a certain process are included or just one or few of them in the analysis, depends on the definition of the system boundaries. Allocation can be based upon mass, commercial value, energy content, or similar product or process features.

3.1.5. DATA QUALITY

Data should be understood as any piece of information that takes part at any stage of the study analysis. The requirement on data depends on the level of details and the desirable depth of the system’s analysis while the quality of data is important for the reliability of the LCA.
Data quality is the specific characteristic of data as expressed through information about the data (metadata), such as information on its uncertainty (spread and pattern of distribution), its reliability (depending on the methods used for measurements, calculations, assumptions and quality control of data), its completeness (number of data collection points and periods and their representativeness of the total population), its age (year of the original measurement), the geographical area for which the data is representative and the process technology or technological level for which the data is representative[26]. Reliability and applicability of the LCA results depends on the quality of the initial data providing the background for assessment and therefore, management of data quality must be an integrated part of life cycle assessment. As the definition of scope and goal of the LCA is identified, data quality management starts with the definition of data quality goals and the strategy of data collection as part of this step. During data collection, data quality is documented for each set of data and through a number of data quality indicators specifies the relation with the data quality goals and the way it is used in the study. Finally, the data quality indicators may be interpreted as an additional uncertainty on the individual data. Such additional uncertainties may be included when calculating the uncertainty of the overall result of the life cycle inventory and may thus be used to give this result a more qualified expression.

The factors that may affect data quality are [5]:

- The source of the data
- The exportation method
- The collection method
- The time collected

The sources may be primary (e.g. direct measurements) or secondary. Secondary sources may be:

- Industrial references
- State reports
- Laboratory test data
- Book references
- Databases and publications
- Relevant LCA studies

The exportation method of the data may be based on:

- Direct and precise measurements
- Estimations and samples
- Models and calculations

The resulted data may be:

- mean values
- monthly or annually values,
- constants or normalized values(based on the exportation method and knowledge)

3.2. LIFE CYCLE INVENTORY(LCI)

In the life cycle inventory (LCI) phase, all data relative to the balance of the system in the form of flows (inflows and outflows) are determined. Data are collected based on the goals of the defined study to quantify inputs and outputs of energy, raw materials, emissions and other releases during the life-cycle of a product or process.

LCI is the most time consuming and resource intensive step for conducting a life-cycle assessment. In every system under LCA, this part of the study is of high importance and requires accuracy and detail of the data collected to avoid any falsification of the final results. Without an LCI, no basis exists to evaluate comparative environmental impacts or potential improvements.

Usually, a flow model is used to represent all flows(energy, raw materials, wastes) and activities(transportation, waste management etc) in and out of the system's boundaries throughout the life cycle. Input and output data are collected for all participating processes of the system and by relating them with the product system ,both energy and material data, to the production of one functional unit, data for each process can be scaled to find the unit process flows, which are required to produce the unit of service(ISO 14041 1998). The life cycle inventory is the sum of all unit process flows in the product system [8].
Calculations and evaluation of the unit process flows are then performed to estimate the total amount of resources used, as well as the generated emissions and pollution in relation to the functional unit. This way, an inventory has been formed including all environmental input and output data of the system under study, with the results able to be depicted in various graphic forms and flows. Life cycle inventory will usually focus on a subset of the resulted data of the hundreds of inputs and outputs being able to produce in the analysis, just to simplify the study. Once the data have been collected, users may decide to refocus the study on the most significant aspects by narrowing the scope and possibly even modifying the goal of the study. This iterative process can reduce the size of the study to a more manageable level, but it runs the risk of missing some impacts[17].
Figure 3.3 below, illustrates the calculation path for the formation of one functional unit of product[5].

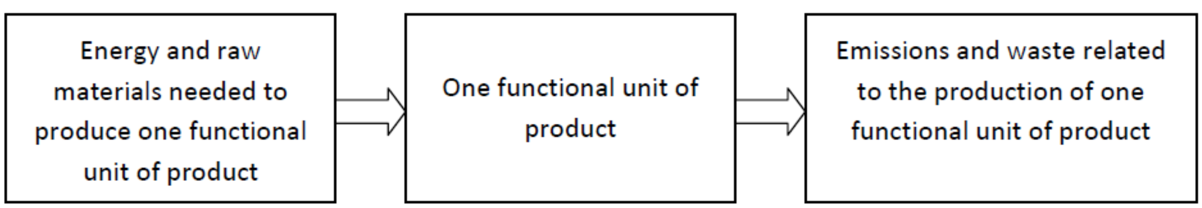


Figure 3.3. Calculation flows of functional unit

For a given system boundary, the flows are differentiated to:
Inflows; those flows coming into the system to be converted into a functional unit

- Energy
- Raw materials
- Water
- Products/co-Products

Outflows; those flows coming out of the system as a derivative of the produced unit

- Emissions to air
- Emissions to water
- Solid wastes
- Byproducts
- Non-Hazardous materials

An LCI will usually record all of the inventory results. After determining those amounts and defining the boundaries of the system the final emissions for the production process are calculated. Many LCA studies, particularly process-oriented, stop at the end of the LCI phase without determining any impact categories. This is perfectly acceptable with simple products, when emitted substances are widely known for their chemical significance by the users. Also, because LCIA methodologies have not yet been developed to characterize the environmental impacts of all substances, it may not be worth the additional effort to try to determine impacts in all cases. Nevertheless for manufactured products where more parts and materials are involved to inventory calculations, specifying and characterizing the results to show environmental impacts and their total effects may be more useful to decision making. Even for process-oriented LCAs, decision makers may want to know the impact of inventory results. The objective of the third step in the LCA is therefore to estimate the environmental impacts of the inputs and outputs of the product or process over its life cycle [17].

3.2.1. KEY STEPS OF A LIFE-CYCLE INVENTORY

According to the published guidance by EPA in 1993 with title, "Life-Cycle Assessment: Inventory Guidelines and Principles" and the document "Guidelines for Assessing the Quality of Life-Cycle Inventory Analysis" in 1995, the framework for performing an inventory analysis was defined with the two documents introducing the following steps of a life-cycle inventory[24]:

- **develop a flow diagram of the processes being evaluated**
- **develop a data collection plan**
- **collect data**
- **evaluate and report results**

The flow diagram(s) developed in Step 1 provides the road map for data to be collected. Step 2 specifies the required data sources and identifies the types, quality, accuracy, and collection methods. Step 3 consists of finding and filling in the flow diagram and worksheets with numerical data. This may not be a simple task. Some data may be difficult or impossible to be obtained, and the available data may be difficult to be converted into the functional unit needed. Therefore, the system boundaries or data quality goals of the study may have to be refined based on data availability. This iterative process is common for most LCAs[24]. Finally, Step 4 corresponds to the accuracy of the results. After identifying the sources, data are collected and organized into various groups and the final task is the verification of accuracy on the results.
The accuracy must be sufficient to support the purposes for performing the LCA study as defined in the goal and scope phase at the beginning of the LCA method.

3.2.2. LCI DATA AVAILABILITY AND VALIDATION

National and multi-national LCA projects around the world are at different levels and various stages of progress, mainly rely on databases provided by private or academic database developers for LCA studies and decision-making. A large number of existing LCI databases mostly preferred by professionals in industrial sector, research centers, governments or consultation offices are listed below in table 3.a[25].

Established LCI databases widely used in LCA practice	GaBi, KCL-Eco, LCAit, SimaPro, SPINE, TEAM, Umberto, etc.
Actual national LCI database projects	Australia, Canada, Germany, Italy, Japan, Switzerland, USA, etc.
Multinational LCI database projects	Cost Action 530, eLCA, etc.
LCI databases that are made publicly available, but were developed within or for industry associations	APME database, etc.

Table 3.a. Existing types of projects and databases

However, there is currently a lack of access to general, publicly available databases. Thus accessibility to databases should be applied with care to complement, strengthen and augment all these important initiatives and databases, and at the same time, avoid duplicating their deliverables.
On the EU level, the big challenge mostly for countries active in the field of LCI data development for a number of years, is to ensure data comparability and exchangeability of a wide variety of existing LCI databases. Moreover, public data accessibility should be accompanied by a quality assurance system to guarantee reliability of the data and continuous

improvement of their quality. LCI analysis results depend mainly in the quality of the LCI data and thus it is of high importance such efforts to yield methodological consistency.
The lack of consistency and transparency makes validation and documentation of the databases difficult [25].

3.3. LIFE CYCLE IMPACT ASSESSMENT(LCIA)

The next phase of an LCA study is the life cycle impact assessment (LCIA) where the environmental impacts of all emissions and extractions are analyzed. More specific, LCIA assesses the potential impacts on human health and the environmental damage associated with the resources used and the emission releases identified during life cycle inventory (LCI). A life cycle impact assessment is a quantitative or qualitative procedure which attempts to link a product or process with the corresponding ecological and human health effects. This is done through impact categories (also called midpoint categories) and pathways by grouping together LCI results with similar causing-effects and in extend the generation of impact indicators depending on the model been used.
The term “midpoint” refers to the impact category, expressing that the impact at this point stands between the LCI result in the middle of the pathway and the endpoint or broader damage at the end of the impact pathway. Endpoints also known as damage categories refer to broader impact categories which represent quality changes in the environment with potential concern.

Five proposed damage categories (endpoints) investigated include damage to[17]:

- **human health**, (diminution of life expectancy, accidents, loss of labor productivity, cost of medical interventions, diminution of the population size, etc.)
- **damage to the biotic natural environment** (wild plants and animals, ecosystems),
- **damage to the abiotic natural environment** (occurrence of natural materials and structures of the non-resource type),
- **damage to biotic natural resources** (wild plants and animals used by humans),
- **damage to abiotic natural resources**, and
- **damage to man-made abiotic environment** (buildings and other structures).

There is no standard or universally agreed-upon set of environmental impact categories (midpoints). However, some commonly identified impact categories include acidification, eutrophication, climate change also known as global warming, nitrification, stratospheric ozone depletion, aquatic toxicity, human toxicity, fossil fuel depletion, water depletion, and land use[25]. In the next paragraph some commonly environmental impacts are analyzed.
Basically, LCIA is the way to translate or convert impact categories (midpoints) to damage categories (endpoints) with the use of indicators, for example to be able to determine tones of CO_2 equivalents (a typically LCI result) to potential impacts on global warming or smog.
In accordance to ISO 14042, table 3.b below presents the proposed LCIA framework with the corresponding definition[25].

Proposed terms for LCIA framework	Definition
LCI results	Outcome of a life cycle inventory analysis that includes the flows crossing the system boundary and provide the starting point for life cycle impact assessment (ISO 14042). LCI results are pressures of the three following types: emissions, resource extraction & uses and physical changes
Midpoint Impact category (Midpoint category)	Class representing environmental issues of concern to which LCI results may be assigned (ISO 14042), involving common or similar processes
Midpoint Indicator	Quantifiable representation of a midpoint impact category (ISO 14042)
Damage Impact category (Damage category)	Class representing damages on an ultimate Areas of Protection to which state/midpoint categories may be assigned (ISO 14042). A benefit is defined as a negative damage
Damage indicator	Quantifiable representation of a damage category
Impact pathways	System of processes, linking the LCI results to state/midpoint indicators and to damage indicators (adapted from ISO 14042)
Areas of Protection	Operational group of items of direct value to human society.

Table 3.b. LCIA framework

3.3.1. LCI DATA AVAILABILITY AND VALIDATION

A given LCIA does not always assess all impact categories but only those that are specified in the scope and goal definition phase at the beginning of the LCA study. The current state of knowledge includes various impact categories, from those that are most commonly evaluated (global warming, eutrophication etc) to those that are less frequently used(noise, casualties etc). This way, LCIA can reduce LCI results(may exceed 200) to a more manageable number of midpoint categories(13 categories).
In this paragraph, the most commonly used impact categories are presented and summarized as state of the art, in 13 midpoint categories[25].

Ozone layer depletion

Various compounds associated with anthropogenic activities released to the air and cause the ozone depletion effect by reducing concentration to the stratosphere. These compounds yield to increasing level of free radicals such as hydroxyl radicals, nitric oxide radicals and atomic chlorine and bromine and characterized by high chemical stability. Chlorofluorocarbons (CFC) is the major compound which accounts for almost 80% of the total ozone depletion in stratosphere. The consequence of this effect is an increase in solar radiation that reaches the earth surface with a large fraction of UVB radiation. Over long periods high exposure to UVB radiation proved to influence human health with diseases like skin cancer as well as animal health, terrestrial and aquatic ecosystems, biochemical cycles and on some materials[25].

Climate change/Global warming

The continuous increase of carbon dioxide in the atmosphere causes the earth temperature to rise rapidly yielding to global warming. CO_2 concentration in the atmosphere absorbs specific wavelength radiation leaving the rest to pass through and heat up the surface of the Earth, altering the energy balance. Greenhouse effect has many types of impacts such as temperature rise, sea level rise, storms, hurricanes, changing the ocean currents, which in turn leads on human health consequences and on biotic natural resources. A well known for science based midpoint indicator is that of Global Warming Potential (GWP) expressed in radiative forcing (W/m^2).

Lastly, according to several studies, Earth's temperature ranges from 0.2 to 0.3 ^{o}C rising per decade which by 2050 will lead to a serious issue with warmer winters and summers, causing significant environmental destructions in the ecosystems[25].

Acidification

Atmospheric substances like sulphur dioxide and nitrogen are responsible for some undesirable effects on terrestrial and aquatic ecosystems (PH variation, detrophication of soils etc.) and by following the chain even human health.

The substances are transformed to sulphuric and nitric acid causing phenomena such as acid rain which influence wetlands and soils degradation.

The affection differs depending on the ability of the ecosystem to absorb and assimilate some depositions[25].

Eutrophication

Some substances such as nitrogen and phosphorus in excess may result to the eutrophication effect. This effect may cause significant problems in the biodiversity mainly with the persistent use of fertilizers resulting to groundwater pollution. For example increased levels of nutrients to an aquatic system may cause extreme generation of phytoplankton (algae blooms).This can result to the depletion of oxygen in the water by blocking solar radiation to the lower levels and thus reduction of fishes and animal population or may experience an increase to specific species which affects negatively the others. Furthermore nutrient surplus on the soil may disturb balance and lead to extinction of rare plants[25].

Human toxicity

Emissions of some substances (heavy metals) to the environment can have huge impacts on human health. Toxicity assessment depends mainly on 3 relative information: tolerable concentration, time of human exposure and toxicological effects. The results are reported in terms of equivalents of a reference substance depending on the polluted medium and the acceptable daily intake for the human health.
There are characterization factors for assessing the toxicological impacts via air and water on human health such as Human Toxicity Potential(HTP) which describes fate, exposure and effects of toxic substances for an infinite time horizon using the reference unit equivalent per kg emission(1,4-DB) [25].

Ecotoxicity

It refers to hazardous toxic substances emitted to the ecosystems and the impacts that caused. Ecotoxicity studies measure the effects of chemicals on fish, wildlife, plants, and other wild organisms, and is been treated in the same way as human toxicity with a few differences. Ecotoxicity Potential (FAETP) is calculated with USES-LCA, describing fate, exposure and effects of toxic substances**,** expressed with the same characterization factors as in human toxiticity (1,4-dichlorobenzene equivalents/kg emission).
The indicator may respond at global, continental, regional or local scale[27].
For further analysis, ecotoxicity can be divided to:

- **Fresh water aquatic ecotoxicity**, refers to the impact on fresh water ecosystems by toxic substances
- **Marine aquatic ecotoxicity**, refers to impacts on marine ecosystems by toxic sybstances
- **Terrestrial ecotoxicity**, refers to impacts of toxic substances to terrestrial ecosystems.

Photo-oxidant formation

It refers to the formation of hazardous substances by natural and man-made activities, such as ozone, which may cause injuries on human health, ecosystems and may damage crops. Ozone on type of smog is a reactive chemical compound in gaseous form, highly toxic, which have proved to cause respiratory distress in people and other mammals. It is formatted under the presence of sunlight reaction on certain air pollutants.
There are two developed models until now as midpoint indicators for smog. The first model on Northern Europe, “Photochemical Ozone Creation Potential(POCCP)” expressed in kg ethylene equivalents/kg emission, and the model in US based on “Maximum Incremental Reactivity(MIR)” measured in units of O_3[25].

Traffic noise

Noise from traffic systems (road, rail, air) is considered as emissions to the environment. High levels of traffic in certain areas and traffic channels under an extended period of time affect the well-being of nearby population causing intolerable noise. Effects may occur to human health(sleep disturbances, work distractions, unproductive work) as well as to natural environment(well being of animals).
The noise effect of a single vehicle or transportation task can be calculated by generally accepted methods[25].

Accidents/Casualties

One of the impact categories that are not frequently used is that of accidents or casualties by physical impacts. Very few LCA studies have considered this impact category, however neglecting damages on human health due to accidents over the life-cycle of a product could lead to biased decisions[25].

Use/Depletion of natural resources

Natural resources such as water, metals, minerals and fossil fuels are very valuable to mankind, allowing us to achieve goals that have an instinct value (welfare, health) as well as enabling human activities.
The extraction and extended use of some natural resources such as water or fossil fuels, can lead to problems on human welfare, human health and ecosystems health. Moreover, this impact indicator may refer to the exhaustibility of some resources and the effects that resource depletion can cause to human and ecosystems health.
The Abiotic Depletion Factor (ADF) is determined for each extraction of minerals and fossil fuels (kg antimony equivalents/kg extraction) based on concentration reserves and rate of de-accumulation[27].

Land use, habitat conservation, bio-diversity

Land use, habitat conservation, bio-diversity, all three correspond to the same impact category with the threat of species extinction both on terrestrial and on aquatic systems driven by loss of habitat.

The total area, the size and shape of ecosystems, the interface between land-water as well as the interconnectedness among them are important factors for preserving populations and the smooth functionality of those systems.
In the oceans, over-fishing seems to be as much a source of species extinction as habitat destruction. A wide range of habitat conservation indicators have been developed in the context of conservation biology (e.g. by UNEP, WWF, SETAC). Relatively little has been done to evaluate bio-diversity indicators in aquatic systems[25].

Dispersal of invasive species

The development of trade as well as tourism and transport goods across borders has accelerated the spread of invasive species (alien to local ecosystems) which affects the local biodiversity.
The new species that invade new foreign habitants may harm the natural flora and fauna influencing directly or indirectly the human health, fisheries, agriculture and food production. The resulting direct impact (midpoint category) is an altered species composition and population volumes, with the indicators primary production and biodiversity-weighted area. The biodiversity indicator should illustrate the level of the negative effects on the native species after introduction in the ecosystem.
The problem of dispersal of invasive species has not been described systematically in the context of LCIA so far, the initial efforts should focus on the description of a generic model, and the collection of data and quantification of the relationships in the model[25].

Waste

This impact category corresponds to the main concerns about inappropriate waste management and the potential pollution on water and air quality as well as on land use and soil, which can greatly influence human health and ecosystems(soil-water contamination, air quality, land use).
Waste may refer to various types such as: municipal waste, industrial waste, hazardous waste or nuclear waste all of high importance at the level of LCI results. Waste indicators positioned between LCI results and the conventional midpoint categories and are very relevant to life cycle management.
A significant number of waste classifications according to different criteria (and therefore many options for waste equivalents) exist and are applied. There is no common practice or agreement on choosing equivalency indicators and factors; it might even be advisable to choose different classification and characterization schemes for different branches or applications[25].

With the introduction of the 13 most generally used impact categories (midpoints), and having described in the previous paragraph the broader impact categories, well known as damage categories (endpoints), the conversion path from LCI results to impact categories becomes better understood during the LCIA phase, and after using specific indicators, finally end up on damage categories (endpoints) assessment. Figure 3.4 below illustrates this conversion from LCI results via midpoint categories to damage categories with all relevant pathways represented by arrows[25].

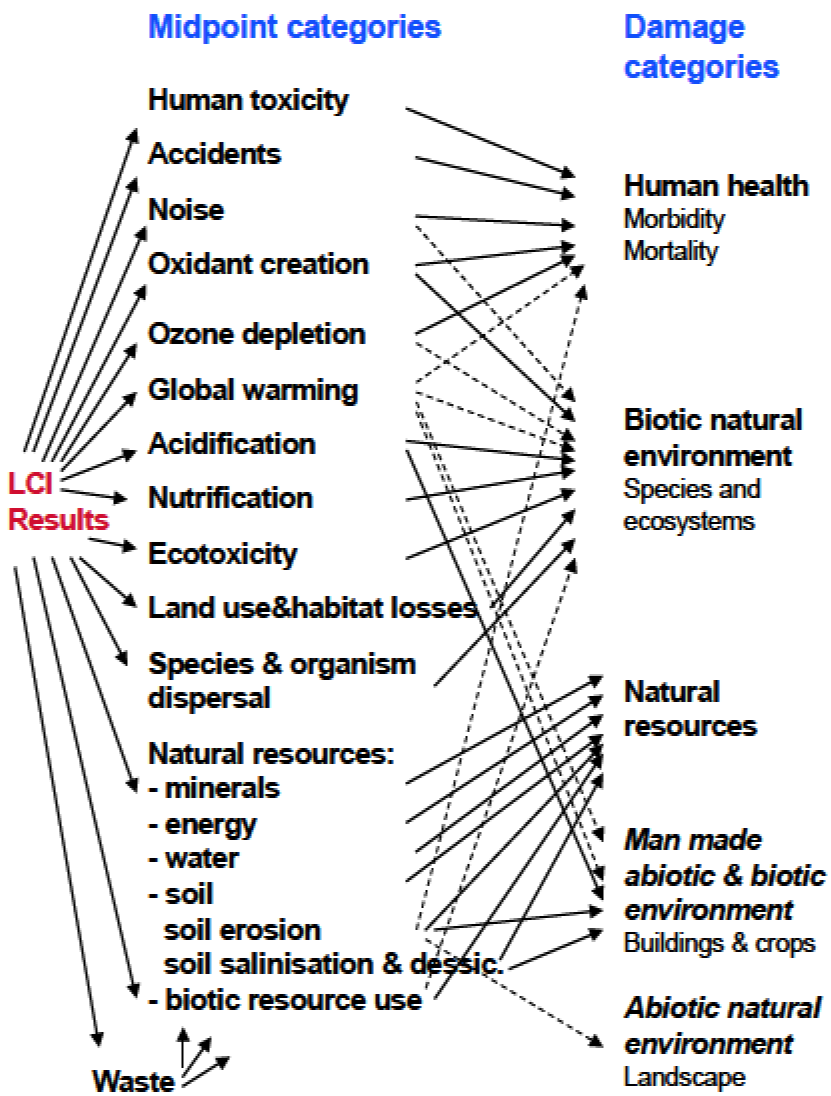


Figure 3.4. Midpoints-Endpoints categories

3.3.2. LCIA STEPS

Life Cycle Impact Assessment (LCIA) consists of the following steps according to ISO 1998:

- *Selection and definition of impact categories*
- *Classification*
- *Characterization*
- *Normalization*
- *Grouping*
- *Weighting*
- *Evaluation of LCIA results*

The first three steps constitute the basic LCIA methodology and are mandatory steps as it is stated by ISO standard, while the others are optional steps depending on the goal and scope definition as it is defined at the beginning of each LCA study. Optional steps, which may be undertaken to refine the results, require additional subjective input. Consequently, the results of these steps have a weaker scientific basis than that of the first three [17].
Below each step is presented and analyzed separately.

Step 1: Select and define impact categories

The first step in an LCIA corresponds to the selection and the identification of all relevant impact categories that will be considered and evaluated as part of the LCA study. This step is directly linked to the goal and scope of the corresponded LCA, and should be able to guide the LCI data collection process as planned. The relevant types of inventory data to be collected in the LCI are specified by the impact categories to be considered.
For an LCIA, impacts are defined as the consequences caused by the input and/or output flows of a system on human health, plants and animals, or the future availability of natural resources. Typically LCIAs focus on the potential impacts to three main categories: human health, ecological health, and resource depletion. Some of the most common impact categories that have been discussed in previous paragraph (3.3.1) are presented in the following table 3.c, with the relevant LCI data for each impact category (classification step) and the characterization factors(characterization step) to follow[24].

Impact Category	Scale	Relevant LCI Data (i.e., classification)	Common Characterization Factor	Description of Characterization Factor
Global Warming	Global	Carbon Dioxide (CO_2) Nitrogen Dioxide (NO_2) Methane (CH_4) Chlorofluorocarbons (CFCs) Hydrochlorofluorocarbons (HCFCs) Methyl Bromide (CH_3Br)	Global Warming Potential	Converts LCI data to carbon dioxide (CO_2) equivalents Note: global warming potentials can be 50, 100, or 500 year potentials.
Stratospheric Ozone Depletion	Global	Chlorofluorocarbons (CFCs) Hydrochlorofluorocarbons (HCFCs) Halons Methyl Bromide (CH_3Br)	Ozone Depleting Potential	Converts LCI data to trichlorofluoromethane (CFC-11) equivalents.
Acidification	Regional Local	Sulfur Oxides (SOx) Nitrogen Oxides (NOx) Hydrochloric Acid (HCL) Hydroflouric Acid (HF) Ammonia (NH_4)	Acidification Potential	Converts LCI data to hydrogen (H+) ion equivalents.
Eutrophication	Local	Phosphate (PO_4) Nitrogen Oxide (NO) Nitrogen Dioxide (NO_2) Nitrates Ammonia (NH_4)	Eutrophication Potential	Converts LCI data to phosphate (PO_4) equivalents.
Photochemical Smog	Local	Non-methane hydrocarbon (NMHC)	Photochemical Oxident Creation Potential	Converts LCI data to ethane (C_2H_6) equivalents.
Terrestrial Toxicity	Local	Toxic chemicals with a reported lethal concentration to rodents	LC_{50}	Converts LC_{50} data to equivalents.
Aquatic Toxicity	Local	Toxic chemicals with a reported lethal concentration to fish	LC_{50}	Converts LC_{50} data to equivalents.
Human Health	Global Regional Local	Total releases to air, water, and soil.	LC_{50}	Converts LC_{50} data to equivalents.
Resource Depletion	Global Regional Local	Quantity of minerals used Quantity of fossil fuels used	Resource Depletion Potential	Converts LCI data to a ratio of quantity of resource used versus quantity of resource left in reserve.
Land Use	Global Regional Local	Quantity disposed of in a landfill	Solid Waste	Converts mass of solid waste into volume using an estimated density.

Table 3.c. Life cycle impact categories

Step 2: Classification

The second step is to group LCI results and classify them to the relevant corresponding impact categories which were formed on step 1(identification of impact categories). This way, simple loads are converted to environmental impacts by summing pollutants that cause the same effect.

Some of those pollutants may contribute to only one impact category while others may participate to more than one impact categories and care must be taken to avoid double counting of same results. For instance, CO_2 emissions is a straightforward assignment to the global warming impact while NO_x emissions can be assigned to human toxicity, photochemical oxidation, acidification and eutrophication impact categories.

According to ISO 1998 there are two ways of assigning LCI results to multiple impact categories depending on whether the effects are independent on each other, or they affect one another[24].

- The first way if independent, is to assign all LCI results to all impact categories. For example since NO_x influence both ground-level ozone formation and acidification at the same time, would be allocated to both impact categories at 100%
- The second way if the effects are dependent on each other, is to find the correct representative portion to the impact categories to which they correspond. For example SO_2 can affect either human health or acidification depending on if the pollutant is on ground level or in atmosphere respectively. Thus SO_2 emissions should be divided between those two impact categories with proportional share (50% to human health and 50% to acidification).

The classification may be qualitative (as reference to direct and indirect impacts) or quantitative (use of specific factors to result to more clear and usable data)[5]. Table 10 in the previous paragraph shows some of the classification correspondence between LCI results and impact categories.

Step 3: Characterization

After matching all LCI results to the appropriate impact categories, they are characterized by using science-based factors to convert them into representative indicators of impacts to human health and the environment. Characterization factors, also called equivalency factors, provide a way to directly compare the magnitude and relevant contribution of the LCI results to each impact category. This way LCI results are quantified through those factors to a common unit for each impact and convert the various inventory inputs into directly comparable impact indicators. Thus, an impact indicator is a quantitative indicator of change that is believed to correlate with one or more actual impacts.

Typically, the following equation is used to produce impact indicators from LCI results and the appropriate converted factors (characterization factors):
Inventory Data × Characterization Factor = Impact Indicators
For instance, all greenhouse gases can be expressed into CO_2 equivalents by multiplying the LCI results by an appropriate CO_2 converted factor also known as characterization factor, to provide an overall indicator of global warming potential(GWP). The use of the characterization factors is that which enables different types and quantities of chemicals to be brought under equal scale to determine the amount of impact each one has on global warming.
An example is given below for better understanding of the equation, for different chemical substances, ending up with comparable results in same units [24].

EXAMPLE. **Characterization of Global Warming Impacts**

Chloroform GWP Factor Value*=9 **Quantity=20 pounds**
Methane GWP Factor Value*=21 **Quantity=10 pounds**

Chloroform GWP Impact= 20pounds x 9=180
Methane GWP Impact= 10pounds x 21=210

GWP= Global Warming Potential
*Intergovernmental Panel on Climate Change (IPCC) Model

In this example the calculation takes place between two different chemical substances, chloroform and methane, with different quantities, assessed for the same impact category. The calculations show that 10 pounds of methane have a larger impact on global warming than 20 pounds of chloroform. The key is to use the appropriate characterization factor which in return will result in correct conversion of the given inventory data to impact indicators. Depending on the contribution of each pollutant to the impact category, there is a relevant appropriate characterization factor to be multiplied with and hence the creation of a common unit for further evaluation or comparison.
For some widely used impact categories such as ozone depletion or global warming, there are commonly accepted characterization factors while in others less used, a consensus is still being developed. A large portion of LCIA research nowadays aims at developing more robust characterization factors, establishing a more stable LCIA model.
Table 10 in the previous paragraph includes possible characterization factors for some of the most commonly used life cycle impact categories [24].
A number of standard impact assessment methods used for the selection of impact categories (midpoint) and their conversion to endpoints are: CML, Eco-indicator, Impact 2002++, BEES, Traci 2, USEtox and EPS 2000, all included in the SimaPro software. Every method applies a different assessment approach which results in different environmental profiles for the systems.

The units of the characterization factors used in CML (typical midpoint method) are defined as follows [17]:

- ***Abiotic depletion****:* unit of characterization factor is kg of antimony (Sb) equivalents per kg of extracted mineral.
- ***Global warming***: unit of characterization factor is kg of carbon dioxide (CO_2) equivalents per kg of emission.
- ***Human toxicity***: unit of the characterization factor is kg of 1,4-dichlorobenzene (1,4-DB) equivalents per kg of emission.
- ***Fresh water aquatic ecotoxicity***: unit of the characterization factor is kg of 1,4-DB equivalents per kg of emission.
- ***Marine aquatic ecotoxicity***: unit of the characterization factor is kg of 1,4- DB equivalents per kg of emission.
- ***Terrestrial ecotoxicity***: unit of the characterization factor is kg of 1,4- DB equivalents per kg of emission.
- ***Photochemical oxidation***: unit of the characterization factor is kg of ethylene (C_2H_4) equivalents per kg of emission.
- ***Acidification***: unit of the characterization factor is kg of sulfur dioxide (SO_2) equivalents per kg of emission.
- ***Eutrophication***: unit of the characterization factor is kg of phosphate ion (PO_4^{3-}) equivalents per kg of emission.
- ***Ozone layer depletion*****:** unit of the characterization factor is kg of chlorofluorocarbons (CFC-11) equivalents per kg of emission.

A properly referenced LCIA will document the source of each characterization factor and each unit, to ensure that they are relevant to the goal and scope of the study. With the end of step 3 of the LCIA, and after finishing with all impact categories, the result is the overall environmental profile of the system under assessment.
Steps one, two, and three(impact category selection, classification, and characterization) that have been described so far, are the backbone of LCIA methodology and are necessary steps for the successful assessment of every LCA study. Optional steps follow thereafter for the completion of the whole LCIA methodology.

Step 4: Normalization

The first of the optional steps to be presented is normalization. In this step the indicator results are normalized by dividing them with a selected reference unit. This technique enables the comparison among different impact categories, to a common dimensionless format related to a reference situation.

Even though it is not a necessary step of the LCIA methodology, it is highly recommended in order to understand the relative importance and magnitude of the results for a process or a product.

There are various methods for selecting a reference value, including[24]:

- The total emissions or resource use for a given area that may be global, regional or local.
- The total emissions or resource use for a given area on a per capita basis.
- The ratio of one alternative to another (i.e., the baseline).
- The highest value among all options.

The method to be used depends in a part on the goal and scope of the LCA study, which may dictate the appropriate reference unit relevant to the targeted results and expectations.

Step 5: Grouping

Step 5 refers to the grouping of impact categories, by sorting or ranking indicators. Grouping is another optional step of the LCIA methodology, a tool used to better facilitate the interpretation of the results into specific areas of concern.

According to ISO 1998 there are two possible ways to group LCIA data[24]:

- Sort indicators corresponding to air and water emissions, or the location of the pollution (e.g. local, regional, global)

- Sort indicators corresponding to a ranking system, such as high, low, or medium priority. Ranking is based on value choices.

Step 6: Weighting

This step of the LCIA methodology "weights" the relative importance of the different impact categories associated with the LCA study. Weighting is a way to emphasize or discriminate the most important category indicators based on opinions of experts or valuation schemes, reflecting goals and scope of the LCA study[8].

In some cases, the impact assessment results alone provide a clean picture with sufficient information for decision-making with obvious results, while in others weighting procedure may ease understanding of the LCIA by pointing the relative significance of the impact indicators. For example, in a location at which eutrophication may not be as much of an issue as human toxicity, a higher weighting factor could be assigned to human toxicity than to eutrophication, while same emission levels in another location may experience completely different weighting factors for human health and eutrophication.
Weighting is not a scientific process and is highly subjective depending on preferability and relevant importance of impact categories which may change with location, time, year or even the nature of the LCA study under assessment. Thus, it is highly advisable that weighting methodology is clearly explained and documented. In general, weighting step consists of the following activities[24]:

- Identifying the underlying values of stakeholders
- Determining weights to place on impacts
- Applying weights to impact indicators

This step is the least developed step of the LCIA methodology, and even that many LCAs use the weighting step, is most likely to be challenged for integrity.
Developing a truly objective or universally acceptable set of weighting methods is not feasible. However, several approaches to weighting do exist and are used successfully for decision-making, such as the Analytic Hierarchy Process (AHP), the Modified Delphi Technique, and Decision Analysis Using Multi-Attribute Theory (MAUT)[24].

Step 7: Evaluation

The last step is that of the evaluation and final report of the LCIA results, which helps gaining a better understanding for the system under assessment. The accuracy of the LCIA results must be sufficient to confirm and support the purposes of the LCA study as defined in the goal and scope section. During documentation of the LCIA results, all assumptions, definitions and boundaries of the system are clearly described as well as the methodology followed for performing LCIA analysis. Although LCIA follows a systematic procedure, due to those assumptions and simplifications, it usually suffers from some limitations. Some of the limitations include [24]:

- Lack of spatial resolution(5000 liters of ammonia release is worse in a small stream than in a large river)
- Lack of temporal resolution(one ton release of particulate substance during a month is worse than the same release spread through the whole year)

- Inventory speciation(inventory listing such as “VOC” or “heavy-metals” do not provide accurate information for environmental impact assessment)
- Threshold and non-threshold impact(ten tons of contamination is not necessarily ten times worse than one ton of contamination)

More complex models may help reduce those limitations with more accurate impact assessment. It is important to document any limitations and further discuss any uncertainties to establish a comprehensive description of the LCIA methodology, with all numerical results to be interpreting the results of the LCA study.

3.4. LIFE-CYCLE INTERPRETATION

The final phase of the LCA process is the interpretation, a technique which identifies, quantifies and evaluates all data used, methods, assumptions, limitations, as well as LCI and LCIA results, by explaining the way that are connected. It refers to the effort done to fully describe and report the final LCA results of the study in a manner understandable and meaningful to the proposed audience, upon which crucial decision-making of a product or process may take place. The decision-makers need to be assured for the reliability and validity of that information, and the best way to achieve this, is by explaining clearly and comprehensively any conclusions drawn from the data.

According to the International Organization for Standardization (ISO), two objectives of life-cycle interpretation are defined[24]:

- Analyze results, reach conclusions, explain limitations, evaluate and provide recommendations based on the findings of the preceding LCA phases and report the results of the life cycle interpretation in a transparent manner.

- Provide a readily understandable, complete, and consistent presentation of the LCA results, in accordance with the goal and scope of the study.

In some cases, it may not be feasible to choose one alternative over the others due to uncertainty in the final results which doesn’t give a clear outcome for an answer. This does not imply that efforts have been wasted. LCA process and the deriving results will still provide decision-makers with a better understanding of the environmental and health impacts associated to each alternative, with information stating the magnitude of each type of impact which in return enables the comparison of the proposed alternatives in the study.

Such information, valuable as well for decision-making, is mostly pointing the pros and cons of each alternative allowing objective evaluation, depending on the goal and scope of the performed LCA study.

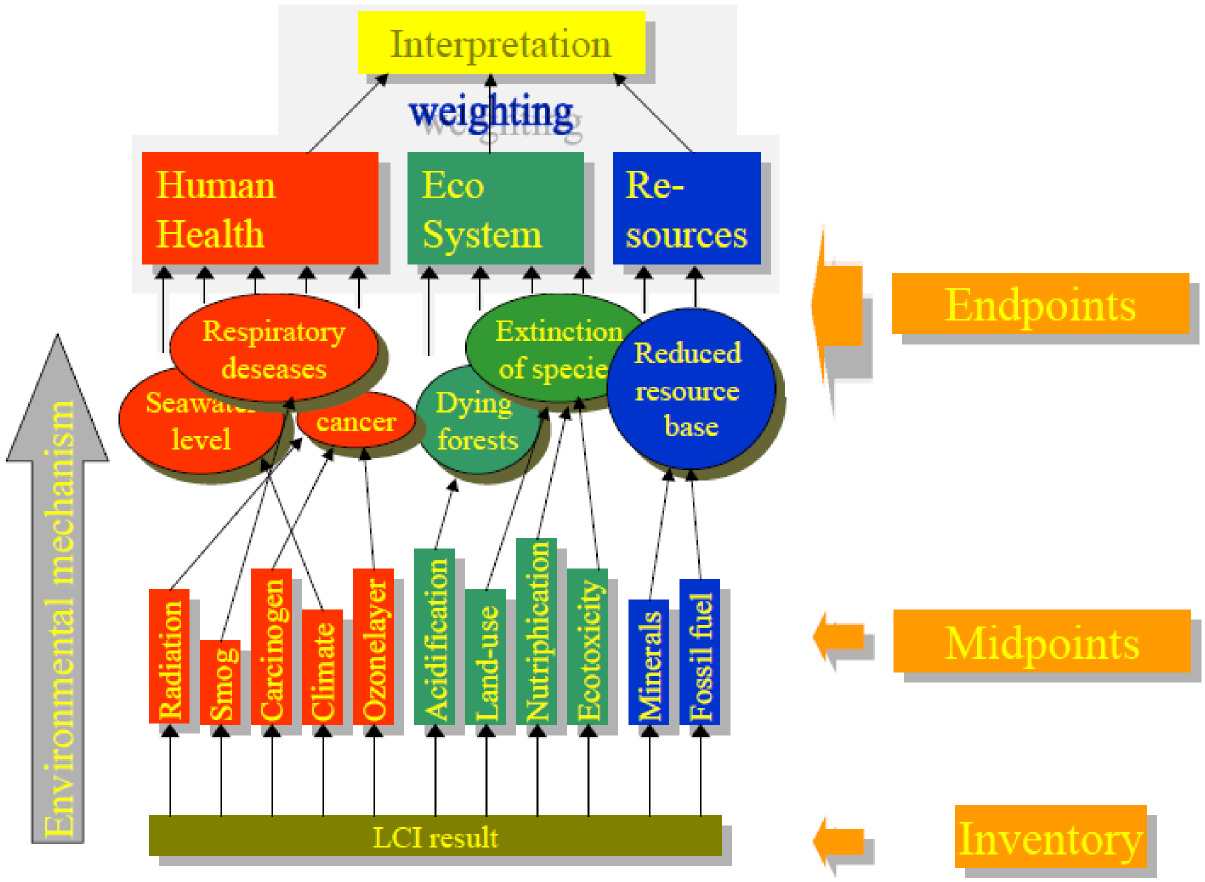


Figure 3.5. Schematic overview

Figure 3.5 illustrates a schematic overview of the methodology and LCA process, from LCI results to the interpretation, by explaining the way that are linked to each other [28].

3.4.1. LIFE-CYCLE INTERPRETATION KEY STEPS

According to ISO's draft standard "Environmental Management-Life Cycle Interpretation" (ISO 1998), the following steps relevant to life-cycle interpretation are identified and presented below[24]:

- Identify Significant Issues
- Evaluate the Completeness, Sensitivity, and Consistency of the Data
- Draw Conclusions and Recommendations

Step 1: Identify Significant Issues

In this first step of the interpretation, all relevant information in the LCA process(study goals, ground rules, boundaries, external involvement, impact categories, results etc) are examined in order to detect those data elements that contribute most on both the LCI and LCIA results regarding a product, process or service. The identification of this information, otherwise known as significant issues, guides the evaluation step(step 2).
Significant issues can refer to[24]:

a. Inventory parameters like energy use, emissions, waste, etc.
b. Impact category indicators like resource use, emissions, waste, etc
c. Essential contributions for life cycle stages to LCI or LCIA results such as individual unit processes or groups of processes (e.g., transportation, energy production)

Specifying significant issues of a product system may be simple or complex. In order to assist this effort of identification, the following approaches are recommended:

- **Contribution Analysis**, the contribution of the LCA stages and processes are compared to the final outcome of the study and examined for relevance.

- **Dominance Analysis**, different kind of techniques and ranking systems(quantitative or qualitative) are used to locate the dominant contributions to be examined for relevance.
- **Anomaly Assessment**, unusual non-expected deviations from the normal values or final outcome of the study are observed and examined for relevance based on previous experience.

Step 2: Evaluate the Completeness, Sensitivity, and Consistency of the Data

The results of the previous effort (identifying significant issues/step 1) are used now to evaluate the completeness, sensitivity, and consistency of the LCA study. This step of the interpretation phase refers to the evaluation of the accuracy and reliability of the LCA results. To assure the fairly comparison among products/processes, the following tasks are recommended[24]:

a. **Completeness Check**, by examining completeness to ensure that all relevant information and data needed for interpretation are readily accessible and complete. Data are usually organized according to various criteria (type, stage of LCA etc)in order to develop a checklist that indicates the most significant parts and areas of the LCA results. This way, it is possible to verify that the results have met the stated goals and scope of the LCA study.

b. **Sensitivity Check**, evaluates the reliability and accuracy of the LCA results by identifying the size of uncertainty and the level that affects the decision-makers ability to confidently draw comparative conclusions. Three common techniques to perform sensitivity check on "significant issues" are presented below:

- Gravity Analysis(Identifies the data with the greatest contribution on the impact indicator results)
- Uncertainty Analysis(Determines impact indicator results by examining the variability of the LCIA data)
- Sensitivity Analysis(Identifies the magnitude on impact indicator results when altering LCI results or characterization models)

c. **Consistency Check**, examines whether the data used during the LCA process are consistent to the goal and scope of the study. All assumptions, methods, limitations or data used during LCA are carefully checked to verify that the study was accomplished as intended and complies with the principals. This way, decision makers have more confidence in the final results.

After completing steps 1 and 2, it has been verified that the results of the impact assessment and the underlying inventory data are complete, comparable, and acceptable to draw conclusions and make recommendations [24].

Step 3: Draw Conclusions and Recommendations

The objective of the final step is to summarize and interpret the results of life cycle impact assessment (LCIA), concluding to the product or process with the least, or alternatively with the most impacts to human health and the environment.
If the LCIA process has stopped at the characterization stage, the results of the impact assessment will have the form of un-normalized and un-weighted impact indicators. In this case the LCIA interpretation is less clear and sometimes further examination may be needed for complex decisions.
In contrary, if optional steps were included in the LCIA process (normalization, grouping, weighting),the impact assessment will return grouped, normalized and weighted data for each alternative, which in this case the recommendation may be simply to accept the product/process with the lowest score. Either way, conclusions and recommendations rest on balancing the potential human health and environmental impact relevant to the study goals and stakeholders concern[24].

Reporting the Results

After LCA has been completed with all previously mentioned phases, a report should be conducted stating all data used, methods, assumptions and limitations in a sufficient and detailed manner to allow the reader (decision-makers, third-party, stakeholders etc) to comprehend the complexities and trade-offs inherent in the LCA study. This report will serve in many different ways, from taking well-balanced decisions regarding a product or process, to as future reference document with scientific value for further research. Either way the report must be complete, reliable, accurate and available as possible, based on the LCA framework with all different phases of the LCA study clearly described. The critical review verifies whether the LCA has met the methodology data, interpretation, and reporting requirements, and whether it complies with the standards.
To summarize with, all components(phases) of an LCA study are presented below in table 3.d, each one followed by the respective definition and purpose, underlying the significance of those four steps that constitute the core methodology of life-cycle analysis[17].

Component	Purpose/Results	Significance/Results/Benefits	Comments
Goal Scope and Definition	Defines purpose of study. Sets boundaries. Establishes functional unit.	Depends on subject and intended use of the study. Sets stage for entire analysis, including quality assurance. Breadth and depth of the study can vary considerably depending on the goal.	Must be clearly specified.
Life-cycle Inventory (LCI)	Provides inventory of input/output data of the system under study.	Data are collected to meet the goals of the study.	Data collection is resource intensive. Data may not be available at level needed. Data may be confidential.
Life-cycle impact assessment (LCIA)	Provides information to understand and assess the magnitude and significance of the potential environmental impacts associated with the inventory results.	Provides a system-wide perspective of environmental and resource issues.	Standard impact categories may not be sufficient to identify and assess all impacts. May need to use software packages that require licensing. LCIA results indicate potential environmental effects; they do not predict actual impacts.
Life-cycle Interpretation	Provides conclusions and recommendations based on the results of the inventory and impact assessments.	Uses a systematic approach to identify, evaluate, and present conclusions to meet the requirements described in the goal and scope.	

Table 3.d. LCA compounds

4. Scope and objective of the study

This chapter includes all necessary information relevant to the purpose of this thesis, revealing the objectives of the study, the functional unit and the software used for the completion of the LCA analysis. It corresponds to the first part of the LCA methodology which sets the groundwork of such analysis, making feasible for the audience to comprehend the nature of the LCA study. This dissertation thesis intends to study the life cycle of the most representative windows (aluminum, PVC, wood, wood-metal) in the market, for their use in both residential and commercial buildings. One of the main scopes of the study is the results to serve as a benchmark for Greece window production, while others are the development of an extensive database which could be a good consultant for decision-makers (purchasers) and supporting tool regarding the environmental performance evaluation of different types of windows. This way, every potential buyer may easily evaluate the environmental impact and compare alternatives to come out with useful conclusions or decisions.
Main objective of this study is the identification and quantification of the environmental impacts, from raw material extraction stage, to the final disposal of the referenced windows. This is achieved by using the methodology of LCA (Life Cycle Analysis). The production processes of these windows are examined thoroughly in order to determine and evaluate their environmental impacts. Other useful objectives aimed by this work are:

- Comparison among the window-types in the entire life cycles
- Identification of the most significant contributors to impacts
- Recognize potential improvements

For the implementation of the study and the exportation of the results the SimaPro software was used. With this software the LCA methodology was applied for the type of frame windows mentioned below:

- Aluminum (double glazing)
- Wood (double glazing)
- PVC (double glazing)
- Wood-metal (double glazing)

The separation of those window types results from the different production processes that are followed and the different materials that are used, taking into account and the transportation needs. Additives and colorants added in panes during production (films, coating), laminated glue, as well as infill gases (argon, crypto, xenon) to strengthen window characteristics are beyond the scope of this study and thus are excluded from the various calculations.

Finally, all information and data used in this study as inflows and outflows that contributed to the environmental impact assessment of the window systems came from:

- Real company data
- Ecoinvent database
- Relevant LCA studies
- Calculated data

This data mix (secondary sources) were gathered and used in a complementary manner to each other, to fill possible lack of information. After been collected, categorized and evaluated, they are imported to the software, to form the pattern of the LCA analysis.

4.1. FUNCTIONAL UNIT

In order to be able to assess all inputs and outputs related to window system under study, the functional unit upon which all calculations will take place should be identified. In this thesis the appropriate functional unit was chosen to be 800mm wide by 1300mm high, as a suitable representative size for the Greek market. The reference window represents a single sash standard casement window (0.8mX1.3m) which enables comparative results to be obtained from the LCA analysis. The other standard options are: double glazed sealed, operable with standard frame profile. It is considered that double-glazed windows are comprising of two normal panes of glass 5mm thick each, and an air cavity of 15 mm thick.

FRAME

Size: 800 mm x 1300 mm
Area: 1.04m^2
Style: Casement, Operable, Single sash
Frame Profile: Standard frame profile (5-15-5)
Lifetime: 25 years
Thermal Transmittance (U-value): 1.6 W/m^{2}K

GLAZING

Glazing: Double glazed
Area: 1m^2
U-value ≤ 1.1 W/m^{2}K

4.2. BOUNDARIES-ASSUMPTIONS

This paper considers frames of different materials (aluminum, PVC, wood, wood-metal) to be assessed on the basis of their production and environmental impacts, all attributable to the following stages that set the boundaries of this LCA study:

- Raw material extraction
- Manufacturing processes
- Assembly of the window
- Waste disposal-Recycling
- Transportation requirements
- Embodied energy/ Fuel use

Each of the above mentioned stages has been evaluated separately and for every frame material individually, to estimate their partial contribution to environmental impacts. The boundaries with nature in this case are the point at which the material is extracted from its natural state and the end state after waste disposal has commenced. Embodied energy refers to the energy used for the production of the window system, which accounts the stages from raw material to the stage of window installation (cradle to gate), and is mainly identified by given data from companies and other relevant studies. Figure 4.1 represents the life-stages of this analysis in sequence from extraction to the final treatment, heat waste and disposal of the windows subassemblies (cradle to grave), followed by the anticipated flows (in, out) of energy used, resources and emissions. The use-phase of windows is excluded from the scope of this analysis, as the focus is on the manufacturing and assembly of different frame windows, and their magnitude on impact categories.
To facilitate the LCA analysis, environmental impacts of painting on aluminum and timber, laminated glue or packaging factors are excluded from this analysis. Same applies for potential impacts that may apply from the use of any machinery which participated on the various stages during windows life-cycle, so efforts may be focused on the most critical processes.
The most important assumption is that all window-types have a useable lifetime of 25 years during which functional properties are retained and once the period of use ended, a material portion is recycled. All calculations performed for the needs of this study are based on average European energy mix, reflecting the situation with more reliable data.

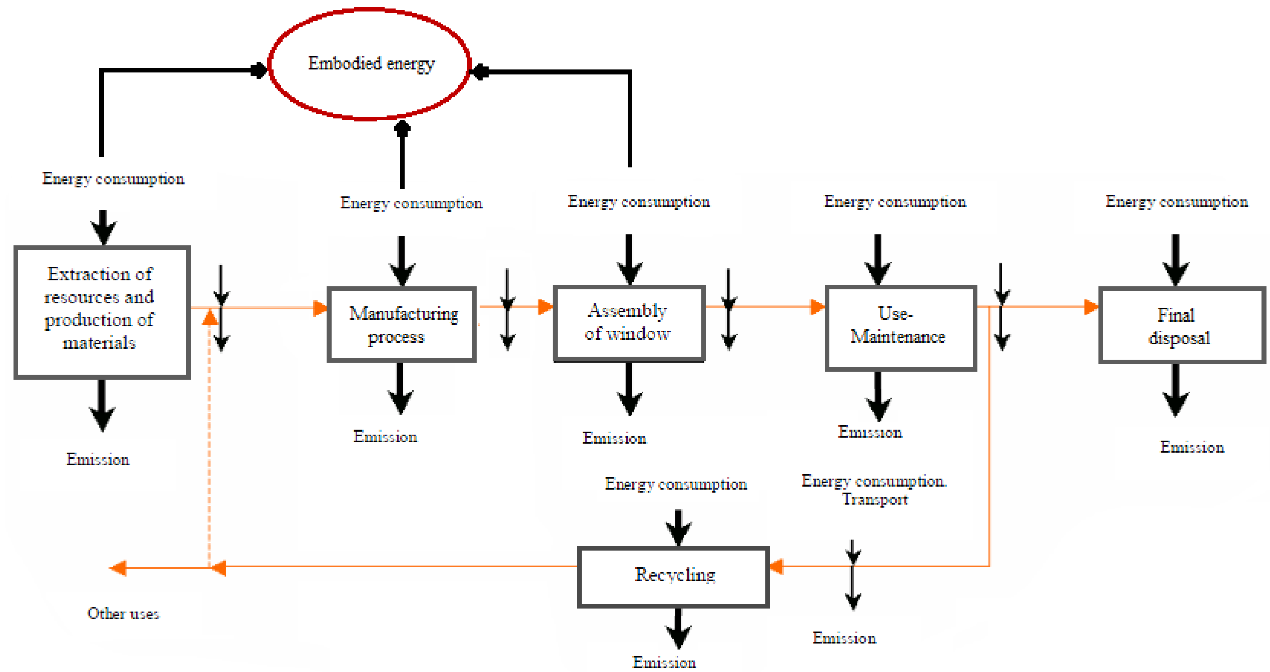


Figure 4.1. Life cycle of a window

4.3. SIMAPRO

SimaPro is one of the most widely used Life Cycle Assessment (LCA) software in the world, allowing you to model products and systems from a life-cycle perspective [28,29]. It offers standardization, so stakeholders will trust your results, as well as the ultimate flexibility so that you can do things your way. SimaPro is a professional tool that helps you build complex models in a systematic and transparent way, so that you can find the best improvement option through various unique features such as parameterized modeling and Monte Carlo analysis (interactive results analysis). SimaPro comes fully integrated with the well known ecoinvent database and is used for a variety of applications, like[29]:

- Carbon footprint calculation
- Product design and eco-design
- Environmental Product Declarations (EPD)
- Environmental impact of products or services
- Environmental reporting (GRI)
- Determining of key performance indicators

SimaPro was selected to complete this LCA as it serves both purposes, calculation of the process flows that represent the window product system, as well as the impacts caused by the numerous inventory values that are established. Based on each window system's available data, the software is differently devised.

4.3.1. ECOINVENT DATABASE

SimaPro come with the full Ecoinvent database covering over 4000 datasets for products, services and processes used in the LCA case studies. This database has been the result of a large effort by Swiss institutes to update and integrate the well-known older LCI databases: ETH-ESU 96, BUWAL250, as well as several other databases. Ecoinvent covers a broad range of data and is considered one of the most reliable databases, well updated, including important information about the production processes (including extraction of raw materials), the waste treatment scenarios and the environmental assessment methods. The figure below shows the Swiss organizations that joined forces to create the Ecoinvent database [28,30].

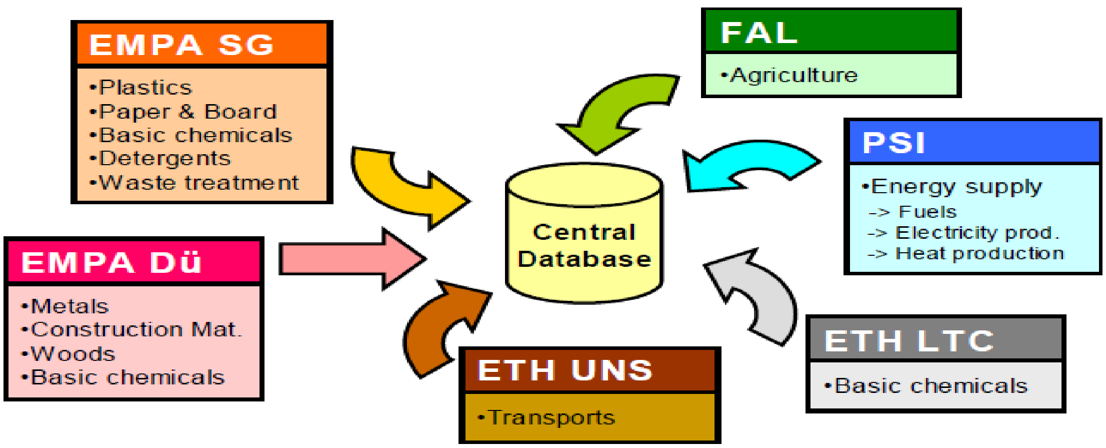


Figure 4.2. Ecoinvent database

4.3.2 CML

In this thesis the CML method was chosen as the appropriate tool to assess the window systems under study. The CML methodology is a typical example of midpoint method (includes ten environmental impact categories) which is used for the assessment of the system's performance and it is applied by the use of the SimaPro LCA software [28]. This method was developed by the Centre of Environmental Science of the Leiden University in Netherlands and is one of the most widely used impact assessment tools. The data needed for the analysis is taken from previous studies, industrial reports and the Ecoinvent database if no other source is available[17]. Some of the characterization factors and the units used by this method were discussed briefly in paragraph 2.3.2(LCIA steps/step 3: characterization).

Normalization was also applied to assess the environmental performance of the window systems. The characterized results were normalized and compared to a reference European situation (Netherlands 1997) applied from this method and is given below in figure 4.3.

Impact category	Normalization factors
Abiotic depletion	5.85 E-10
Acidification	1.49E-9
Eutrophication	1.99E-9
Global warming (GWP100)	3.96E-12
Ozone layer depletion (ODP)	1.02E-6
Human toxicity	5.32E-12
Fresh water aquatic ecotoxicity	1.33E-10
Marine aquatic ecotoxicity	3.14E-13
Terrestrial ecotoxicity	1.09E-9
Photochemical oxidation	5.49E-9

4.3. Reference situation-Netherlands 1997

The results become dimensionless and the comparison of different impacts becomes possible in order to understand the relative importance and magnitude of the results for a process or product.

5. Environmental performance of window frames

In this chapter the LCA method is applied to the manufacturing process (raw materials extraction-transportation-assembly) of four widely used frame materials for windows: aluminum, PVC, wood and wood-metal. After introducing each frame-case and defining the inventory and all participating processes respectively, a comparison among them takes place to identify the relative impact contribution of each one of them to the environment.
As it was defined in the part of the goal and scope, the functional unit is a window frame of 1m^2 visible area, and common thermal transmittance (U value) for all frame-cases equal to 1.6 W/m^{2}K.
In this thesis, the focus is directed in the partial life cycle of the product, from resource extraction to the factory gate(cradle to gate), followed by all relative impact categories, while a comparison in the end is necessary, to illustrate the magnitude of the processes in LCA that are directly related to manufacturing of the frame material. The dataset used by Simapro software describes all input materials and processes to produce 1 m^2 of a referenced case window of each frame, with the assumption of 25 years useable lifetime.

5.1. ALUMINUM FRAME

Aluminum production[9] is one of the most energy intensive processes(primary-225MJ/kg) in comparison to other frame materials(wood, PVC) and during its process huge amounts of dangerous pollutants are emitted to environment like, carbon dioxide (CO_2), polyaromatic hydrocarbons(PAH_s), acidic sulfur dioxide(SO_2) and dust. It is the third most abundant metal in nature and the chief ore is bauxite. Primary aluminum is produced from raw bauxite entirely, and secondary is that produced from recycled aluminum. Theoretical is 100% recyclable without any losses on its properties and the energy needed for recycling is about 5-7% of the energy used for primary aluminum production from its ore.
Aluminum windows are characterized by the light weight and durability through time. The cost in general is low and the maintenance needed is almost none, thus is an affordable window type, cost attractive, with many property possibilities depending on window composition. However aluminum windows are highly thermal conductive and in order to improve the insulation capability of the windows, a thermal break made usually from plastic is incorporated into the frame to reduce the direct conductivity between the inside and outside parts of the windows.

Figure 5.1. Aluminum window frame.

This dataset describes all the processes and material inputs needed to produce an aluminum window frame with 1 m2 visible area, weighting 50.7 kg. Included processes are section bar rolling for steel parts and fittings, section bar extrusion for aluminum parts, extrusion of HDPE plastic, surface treatment (powder coating), all the road transport at different production phases, the heat waste and the disposal of the plastic cuttings. Figure 5.1 below shows the structure of aluminum frame production, from the extraction of raw materials (bauxite) to the complete manufacturing and assembly of the window frame, describing highly automated technology processes in window frame manufacturing.

The total energy input required to produce and process 1 kg of formed aluminum that is utilized for frame window is much debated and varies from 50- 225MJ/kg(primary or secondary) , with the most energy intensive processes to be smelting and electrolysis from primary aluminum production.

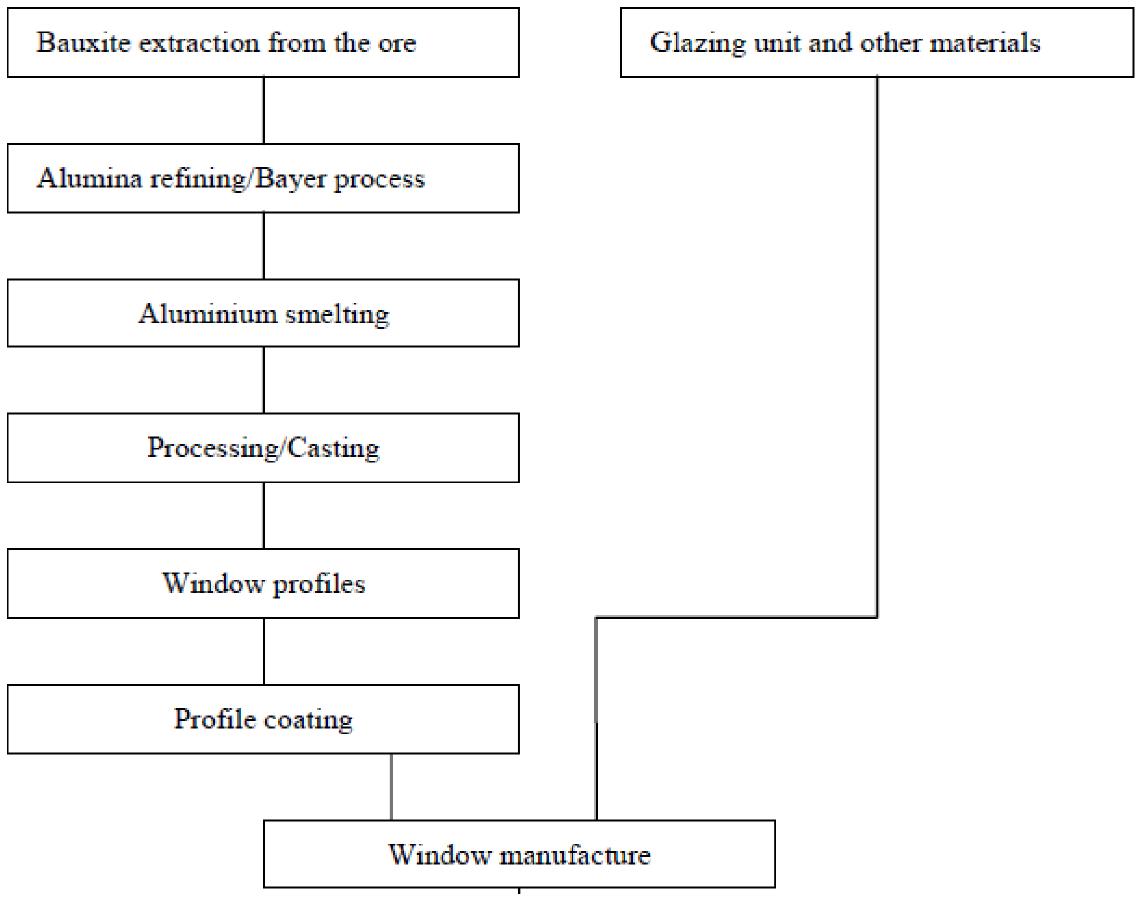


Figure 5.2. Production of aluminum frame.

The production process for this frame-case, the materials used and the characterized results are shown in the following flowchart (figure 5.3). Input data (materials-fuels) were exported from SimaPro and refer to the inventory of this analysis, representing all inflows in order to form one production unit, in this case 1m^2 of aluminum frame. Outputs refer to the impact categories and associated indicators that specify the emissions contribute to soil, water and air, and waste heat at the end. The characterized results correspond to ten impact categories, otherwise known as midpoints, based on the assessment method which in this case is CML2 Baseline. It should be noted that normalization, an optional step of the LCA methodology which is also included in CML2 Baseline, is then used for a dimensionless comparison to a reference state between the different impact categories.

Inputs(materials-fuels)

Synthetic rubber, at plant 4.87 kg
Reinforced steel, at plant 0.516 kg
Chromium steel 18/8, at plant 0.457 kg
Powder coating, aluminium sheet 9.8 kg
Section bar extruction, aluminium 38 kg
Section bar rolling, steel 0.975 kg
Extrusion, plastic film 0.246 kg
Polyethylene, HDPE, granulate, at plant 0.246 kg
Electricity, medium voltage, production UCTE at grid 1.27 kwh
Isopropanol, at plant 0.0208 kg
Transport, lorry>16t, fleet average 4.57 tkm
Glass fibre reinforced plastic, polyamide, injection moulding at plant 5.27 kg
Acrylonitrile-butadiene-styrene copolymer, ABS, at plant 0.4kg
Nylon 6, at plant 0.0146 kg
Aluminium, production mix, at plant 39.7 kg
Adhesive for metals, at plant 0.29 kg
Metal working factory 2.32E-8 p

Final product

Aluminum frame 1m^2/ U= 1.6W/m^{2}K

After end of life

Waste to treatment

Disposal, plastics, mixture,15.3% water, to municipal incineration 0.102 kg
Disposal, building, polyethylene/polypropylene products, to final disposal 0.246 kg

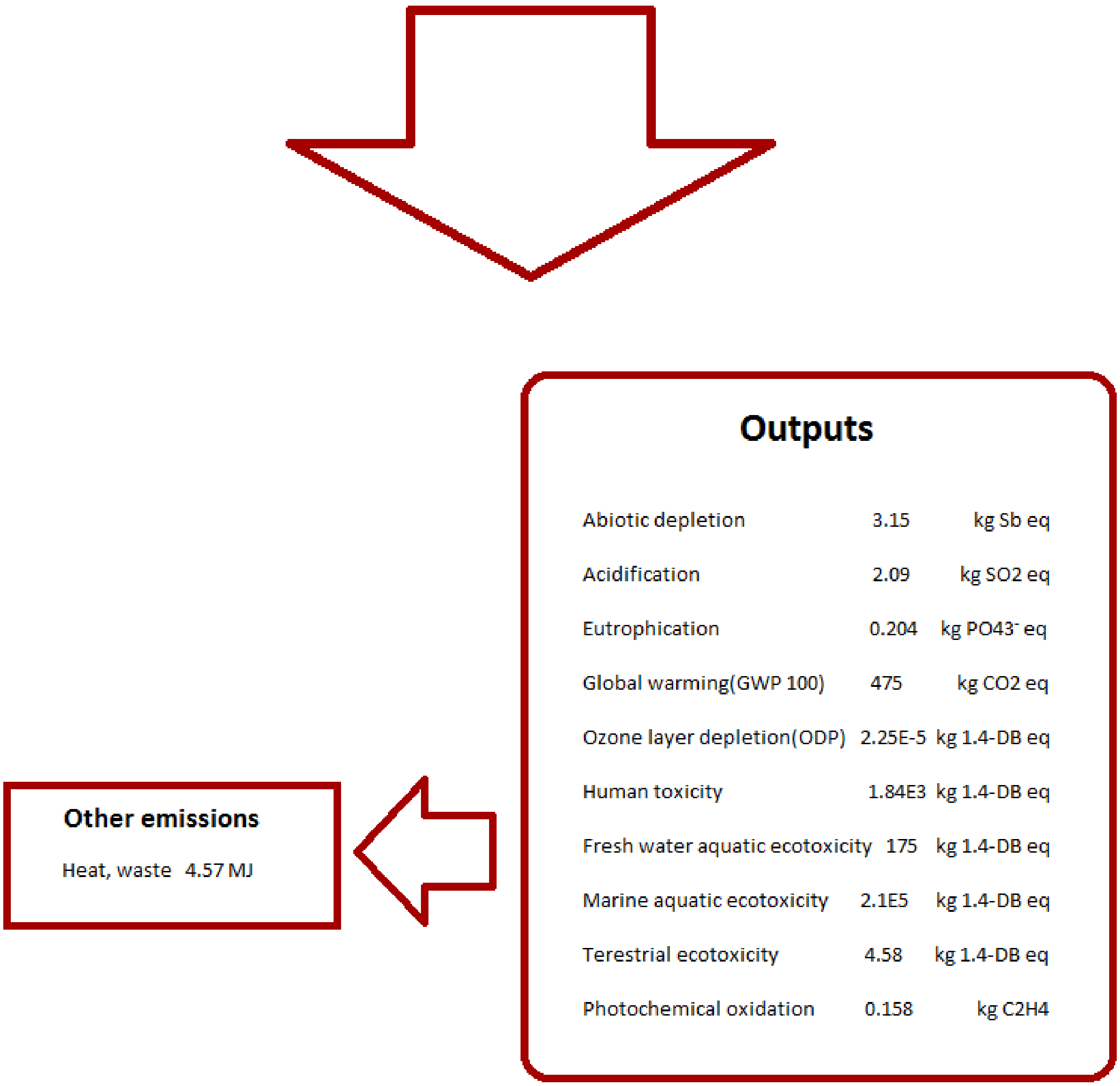


Figure. 5.3. Production process, materials and characterized results per m^2 of aluminum frame.

As shown in the following diagram (Figure 5.4), which represents the contribution of each part of the frame in all impact categories respectively, the aluminum mix that is used for the production is more than 50% of each impact. This is mainly explained by the complex and energy intensive processing for the production of the aluminum (primary).

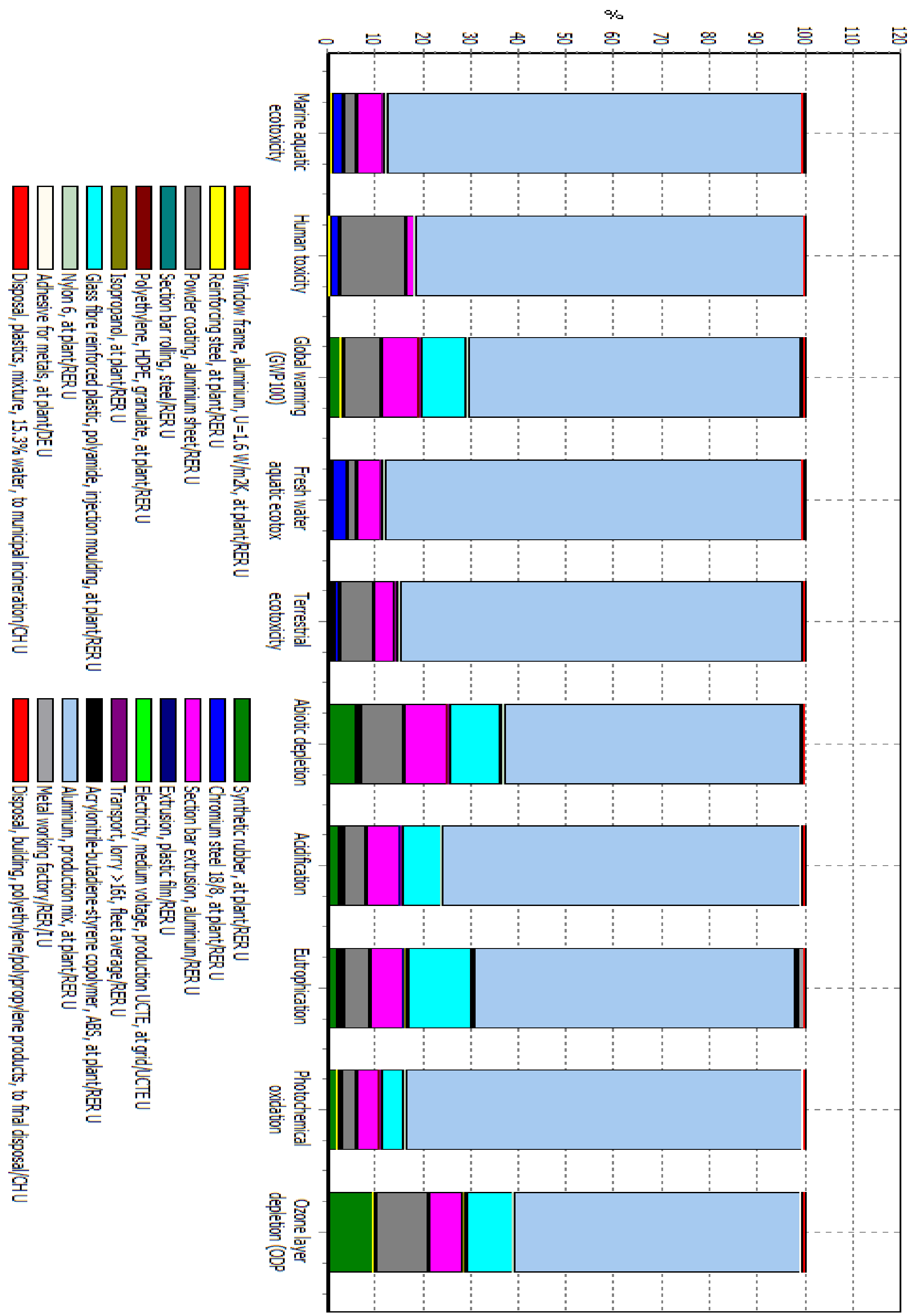


Figure 5.4. Input data (materials-fuels) contribution to impact categories (midpoints) for the production of aluminum frame.

The normalization of characterized results is a procedure needed to show the order of magnitude of the environmental problems generated by the products life-cycle. To achieve that a common dimensionless format is needed to enable the comparison of different impact categories. Figure 5.5a below depicts the transformation of characterized to normalized results for every impact category.

Characterization

Abiotic depletion	3.15	kg Sb eq
Acidification	2.09	kg SO_2 eq
Eutrophication	0.204	kg PO_4^{3-} eq
Global warming(GWP 100)	475	kg CO_2 eq
Ozone layer depletion(ODP)	2.25E-5	kg 1.4-DB eq
Human toxicity	1.84E3	kg 1.4-DB eq
Fresh water aquatic ecotoxicity	175	kg 1.4-DB eq
Marine aquatic ecotoxicity	2.1E5	kg 1.4-DB eq
Terestrial ecotoxicity	4.58	kg 1.4-DB eq
Photochemical oxidation	0.158	kg C_2H_4

Normalization

Abiotic depletion	1.99E-11
Acidification	6.47E-12
Eutrophication	1.54E-12
Global warming(GWP 100)	1.08E-11
Ozone layer depletion(ODP)	2.93E-14
Human toxicity	3.08E-11
Fresh water aquatic ecotoxicity	8.46E-11
Marine aquatic ecotoxicity	2.77E-10
Terestrial ecotoxicity	1.74E-11
Photochemical oxidation	1.51E-12

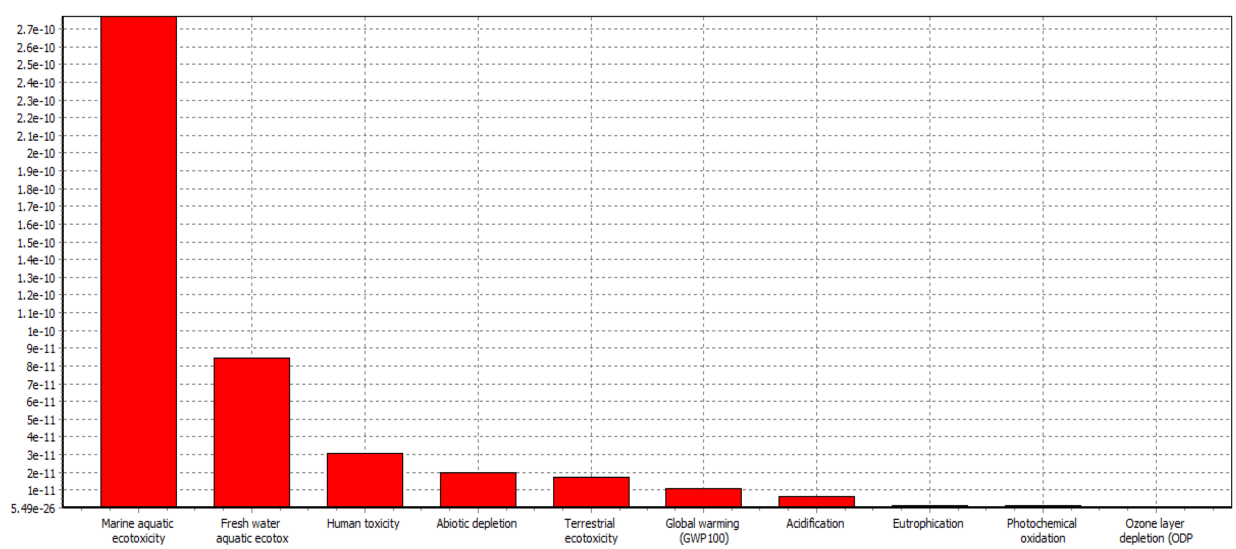


Figure. 5.5. Normalization of characterized results and magnitude to impact categories.

Marine aquatic ecotoxicity (2.77E-10) proved to be the main affected impact category from the manufacturing process of aluminum, while the least is the ozone layer depletion(2.93E-14). Figure 5.5b shows the order from the most to the least contributing emissions, compared to a reference European state(Netherlands 1997) during the production stage of $1m^2$ of aluminum frame.

5.2. PVC FRAME

Polyvinyl chloride [9], commonly abbreviated as PVC, consists of chlorine, carbon and hydrogen and is the third-most widely produced plastic. It is a synthetic material and is derived mainly in the biggest part from fossil fuels like natural gas and petroleum.
During the production consumes big amounts of energy (70MJ/kg) but is not as energy intensive process as aluminum's.
The biggest drawback of this material is the poisonous pollutants such as vinyl chloride, hydrocarbons, heavy metals and dioxins during the production phase.PVC also decomposes really slowly and as a waist contains environmentally dangerous substances. The recycling process during the life end of a product consisting from PVC is a complex procedure due to the presence of additives and several reinforcement materials.
PVC window have a wide range properties, depending on the additives on the final product. Additives can be plasticizers for improving the processing and reduce brittleness or stabilizers to protect against heat, oxidation and ultraviolet radiation (solar radiation) causing the degradation of the window.
The overall thermal conductivity of PVC windows is low and when metal reinforcements are used to increase the rigidity of the frame, may end up increasing the overall conductivity. Generally PVC suffers from high temperatures and ultraviolet radiation which may break the molecular bonds and as a matter of that the embrittlement and discoloration of the product.

Figure 5.6. PVC window frame

A PVC frame is made of hollow profiles joined with heat, or solvent welded. Oxychlorination is the process where ethylene, hydrogen chloride and air are heated in the presence of copper catalyst to give the main substance of PVC, the so called vinyl chloride. PVC windows are stable in saline and polluted air, while they have high coefficient of thermal expansion (two to three times higher than aluminum).

This dataset describes all the processes and material inputs needed to produce a plastic window frame with 1 m2 visible area, weighting 94.5 kg. Included processes are injection molding and extrusion of PVC, section bar rolling for steel fittings, section bar extrusion for aluminum parts, all the road transport at different production phases and the process heat waste. Figure 5.7 below depicts the general flowchart of PVC production stage, from raw material extraction (vinyl chloride, carbon, hydrogen) to the final assembly of the PVC frame, describing highly automated technology processes in window frame manufacturing.

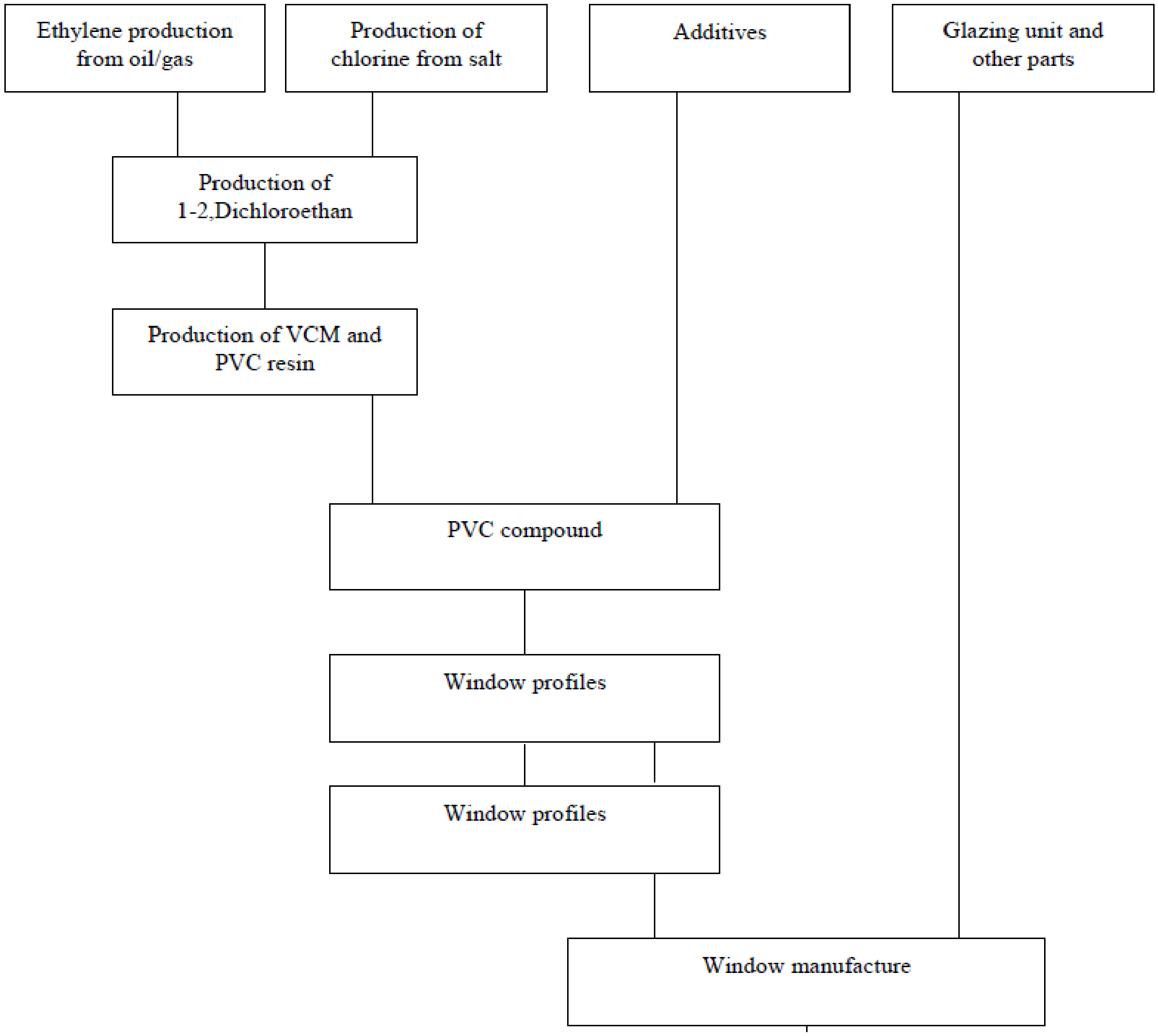


Figure. 5.7. Production of PVC

The following flowchart in figure 5.8, corresponds to the specific production process of PVC frame. All inventory inputs such as materials, fuels and energy used, are taken into account with SimaPro, in order to produce 1m^2 of PVC frame of U value 1.6W/m^{2}K. Outputs are characterized results which represent each impact category, and indicate the level of influence that PVC production has to the environment. The damage categories are then normalized on a reference European level to estimate the relative importance of the manufacturing process to each category.

The total energy input (embodied energy) for the production of 1m^2 PVC frame window is estimated to be 13.8 kWh(50 MJ), while the all road transport at different production phases was calculated to be 30.5tkm.

Inputs(materials-fuels)

Chemicals organic, at plant 0,0287 kg
Synthetic rubber, at plant 0.798 kg
Zinc coating, coils 2.11 m^2
Copper, at regional storage 0.00698 kg
Polystyrene foam slab, at plant 0.184 kg
Section var extrusion, aluminium 1.1 kg
Section bar rolling, steel 37.9 kg
Steel, low-alloyed, at plant 38 kg
Zinc coating, pieces 0.463 m^2
Zinc, primary, at regional storage 0.463 m^2
Polyethylene, LDPE, granulate, at plant 0,00578 kg
Polypropylene, granulate, at plant 0.219 kg
Polystyrene, high impact, HIPS, at plant 0.208 kg
Injection moulding 1.9 kg
Transport, lorry 20-28ft, fleet average 30.5 tkm
Electricity, medium voltage, production UCTE, at grid 13.8 kWh
Polyvinylchloride, at regional storage 58.4 kg
Extrusion, plastic pipes 54.3 kg
Aluminium, production mix, at plant 1.1 kg
Metal working factory 4.32E-8 p

Final product

PVC frame 1m^2/ U= 1.6 m^2K

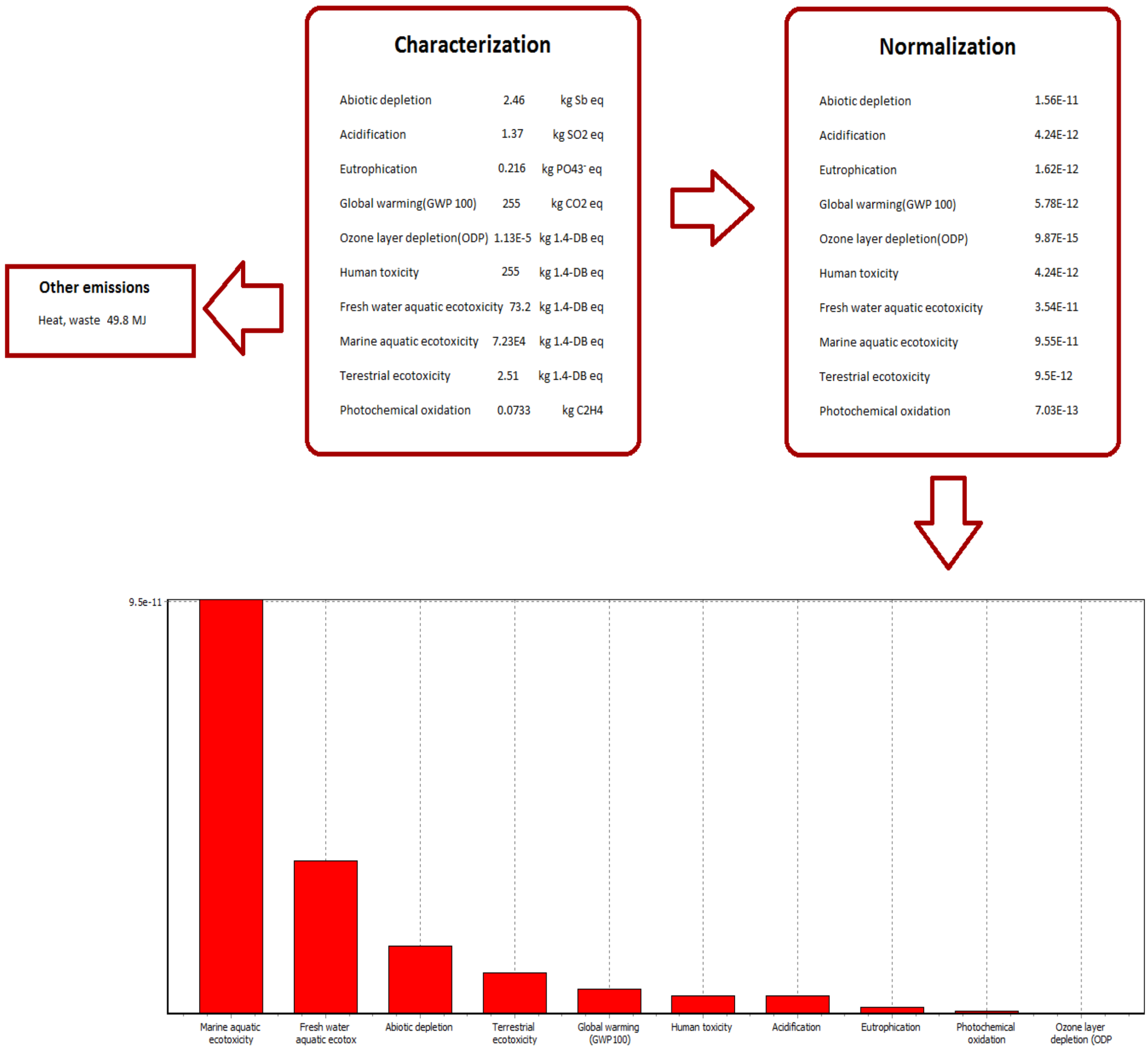


Figure 5.8. Flowchart and magnitude to impact categories per m^2 of PVC frame

Marine aquatic ecotoxicity(9.55E-11) is the dominant impact category(in relevance to the reference situation) as it is shown above in figure 5.8b after the normalization of the resulted data, while the least influenced category is that of ozone layer depletion(9.87E-15). This caused by the highly dangerous substances that can seep into soil and water.

The diagram below in figure 5.9 gives the share of all contributed parts of PVC frame to each impact category respectively. The most hazardous parts to all ten impact categories appears to be the steel low alloyed and the polyvinylchloride which has a complex process in order to gain it.

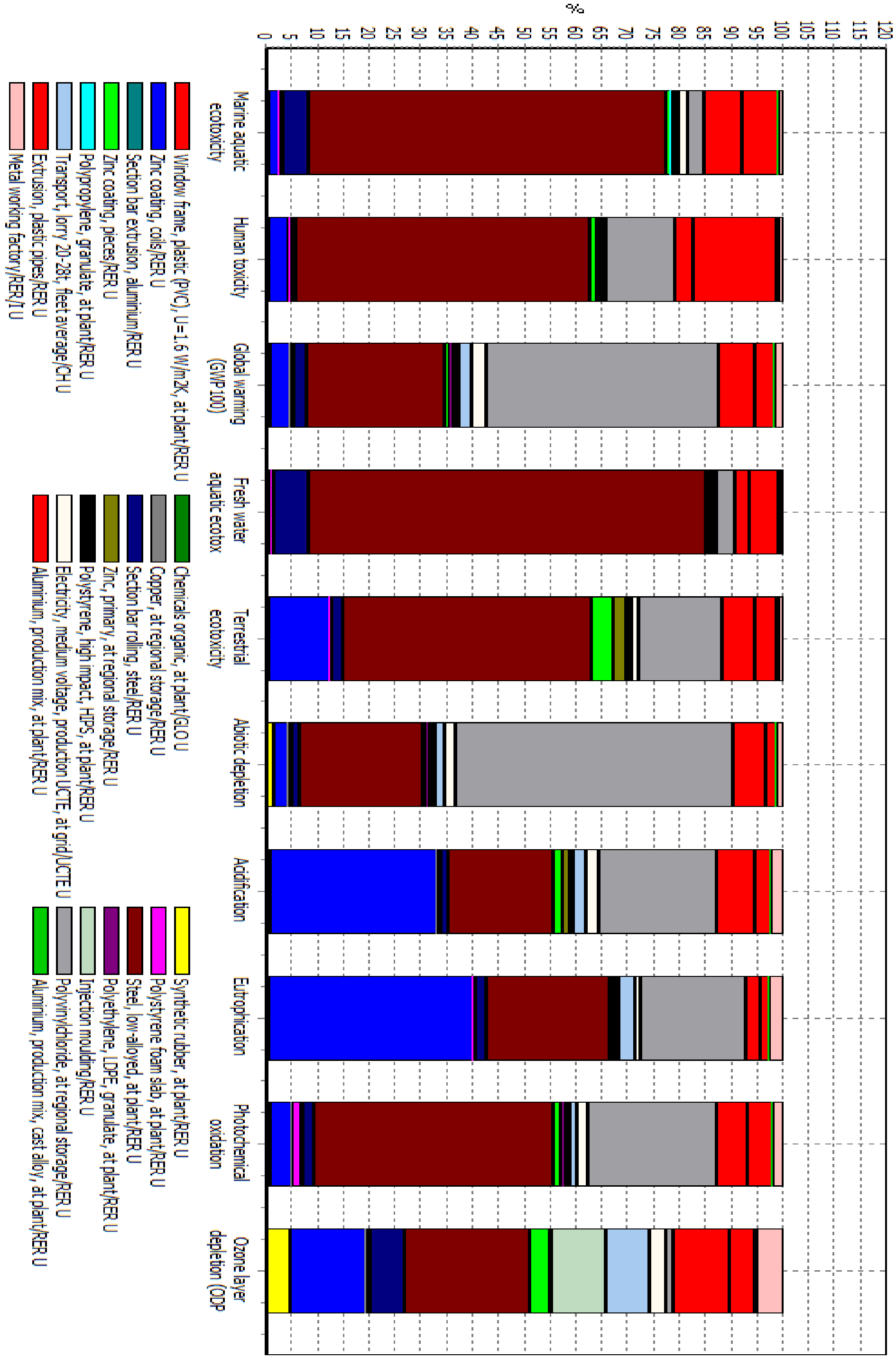


Figure 5.9.Input data (materials-fuels) contribution to impact categories (midpoints) for the production of PVC frame.

5.3. WOODEN FRAME

Timber[9] is the least crafted material between others and the easiest to process. Lumber (also known as timber) is wood in any of its stages from felling to readiness for use as structural material for construction. It mainly consists from lignin and cellulose and its composition differs depending on the type of the tree. From tree to tree organic substances such as proteins, sugar resin and water differs giving small scale differences on the final lumber.
The felling of trees, either softwood or hardwood, have many effects on the environment. Thus the environmental concern nowadays is high, with the introduction of sustainable forest management. For every tree that is felled, another two at least are planted. Having that in mind we are referring to a slow but kind of renewable cycle, defining timber as a renewable material. The embodied energy of timber is relatively small (3-5.5MJ/kg), using less primary energy than the market alternatives, PVC and aluminum.
Is the oldest window frame material in use, nominating as the most traditional among others. Timber as a material possesses good thermal and sound insulation, it is easily processed and formatted for various applications, doesn't corrode and given the right treatment doesn't rot. On the other hand, timber woods have to be painted and maintained every few years otherwise weather conditions and moisture will deface them in a short life-period.

Figure 5.10 Timber window frame

This dataset describes all the processes and material inputs needed to produce a wooden window frame with 1 m2 visible area, weighting 80.2 kg. Included processes are timber sawing, varnishing (primer, solvents, paint), section bar rolling for steel fittings, joining, fitting, all the road transport at different production phases and the disposal of paint remains. The following figure (5.11) illustrates the general flow-chart of timber frame production, from the extraction of raw materials (wood etc) to the final construction and assembly of the frame. The required energy input per kg of wooden frame is approximately 5MJ/kg, and is classified as the least energy intensive material for processing.

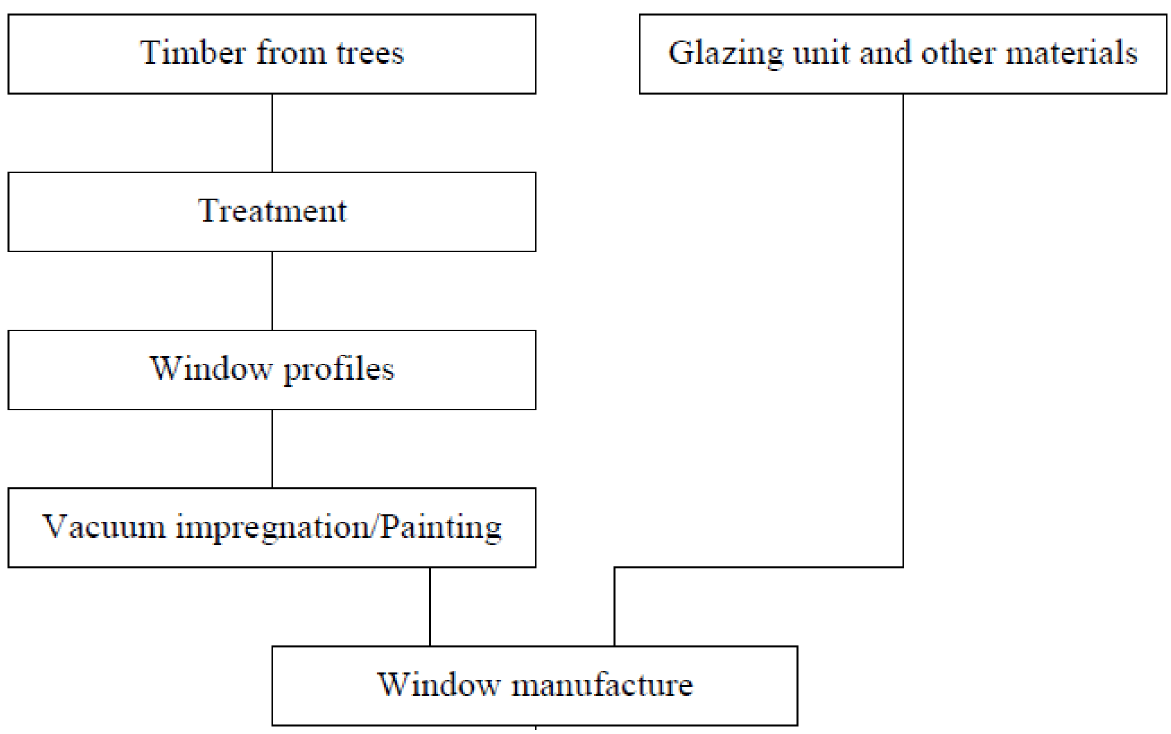
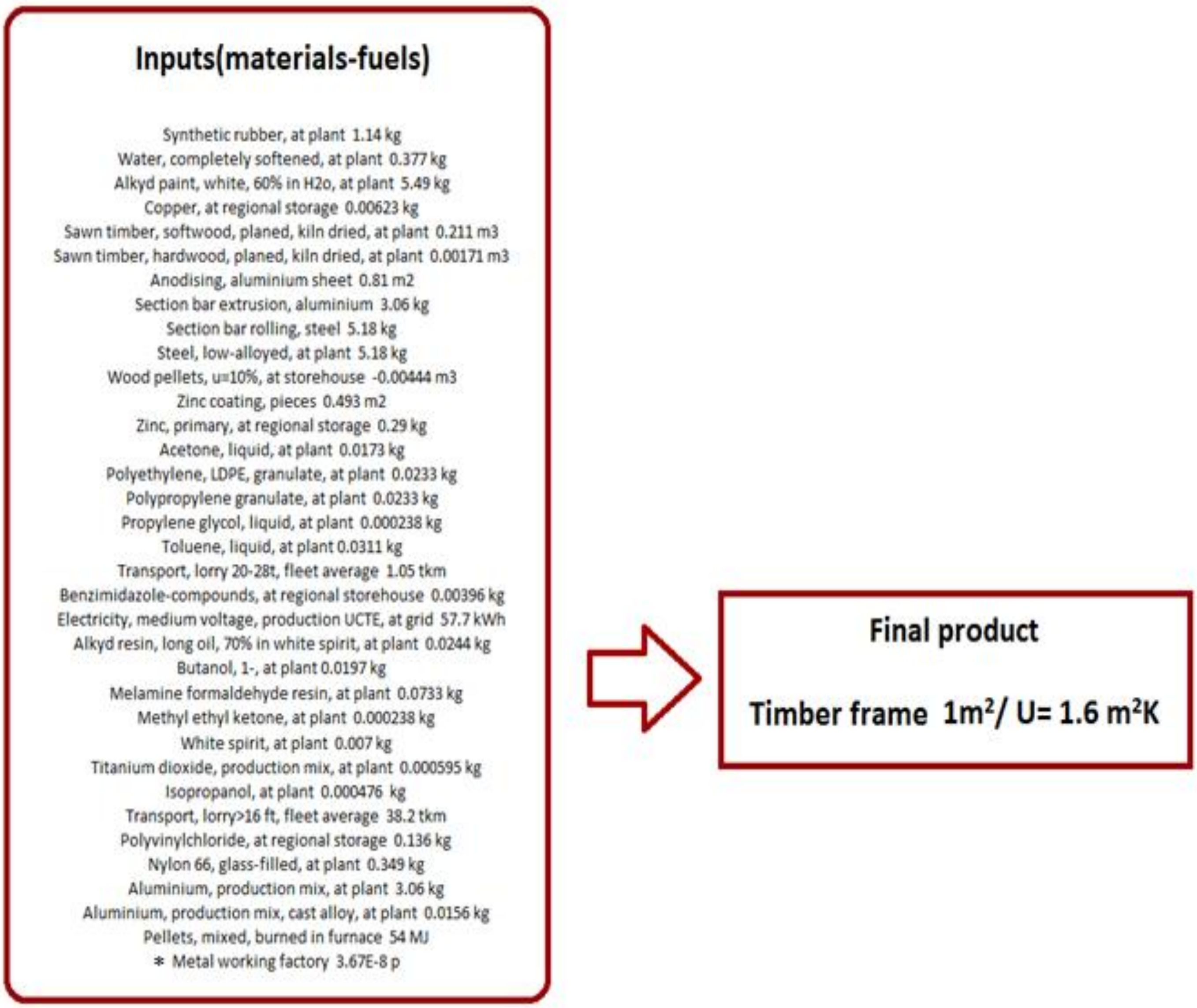


Figure 5.11 Production of wooden frame

The production process for $1m^2$ of timber frame with U value equal to $1.6W/m^2K$, the materials used and the characterized results are shown in the following flowchart (Figure 5.12). The normalized results next, show the order of magnitude of the environmental problems generated by the product's life-cycle, compared to the total environmental loads in Europe(reference state, CML set/ Netherlands 1997).



* "p" is the symbol for 1 item or unit(free mass unit)

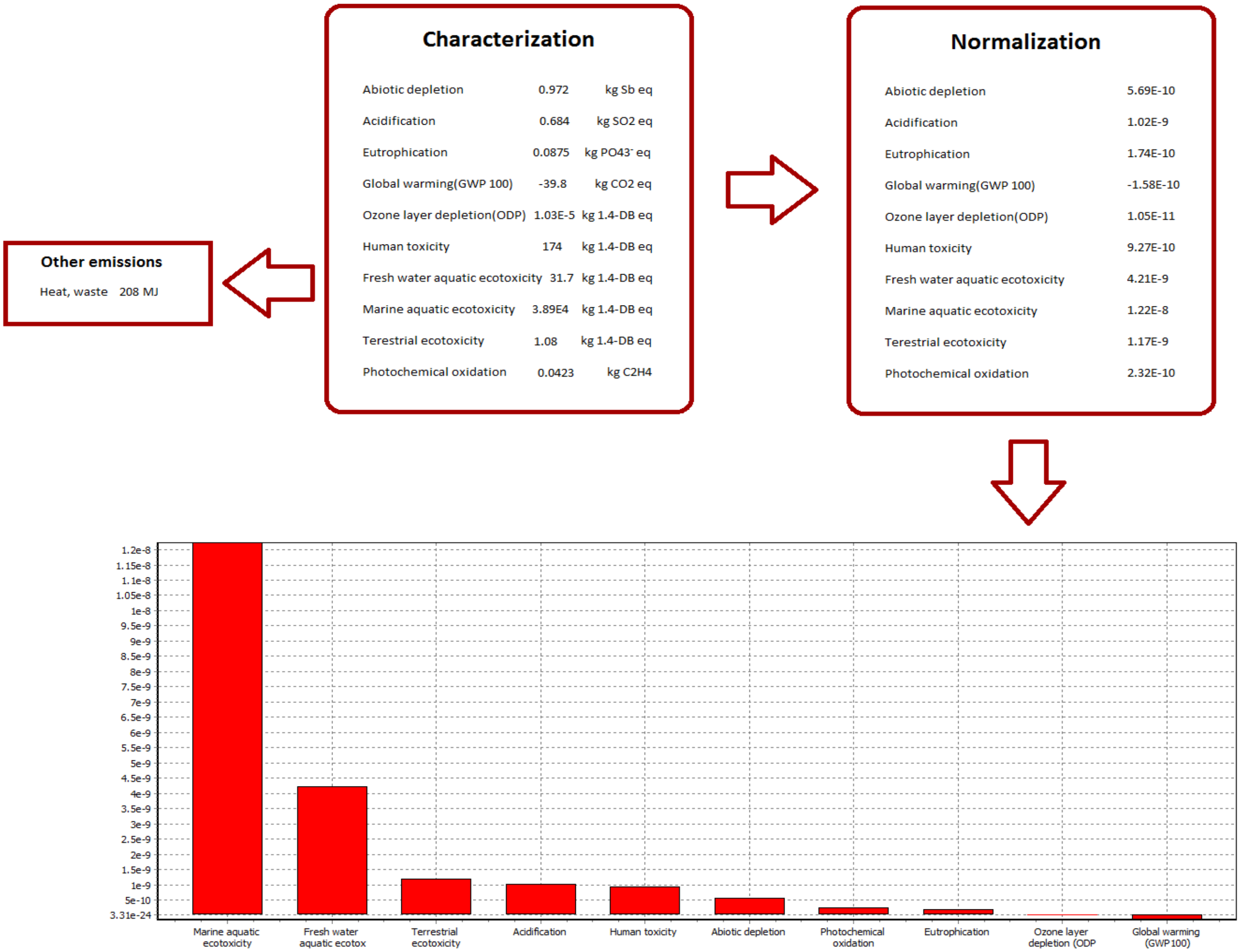


Figure 5.11. Flowchart and magnitude to impact categories per m^2 of wooden frame

The negative value regarding global warming potential derives from the fact that growing forests act as carbon sink, meaning they extract more CO_2 from the atmosphere in tree growth than the CO_2 released during their life-cycle. After the normalization of the results and the comparison to the European benchmark (Netherlands 1997), marine aquatic ecotoxicity appears to be the most disordered category, while lastly the global warming has a positive impact.

The next diagram (figure 5.12) gives the partial contribution of inputs to each impact category. Softwood and steel alloyed have a considerable share in most impacts. Attention should be paid to the “positive” negative impact of global warming.

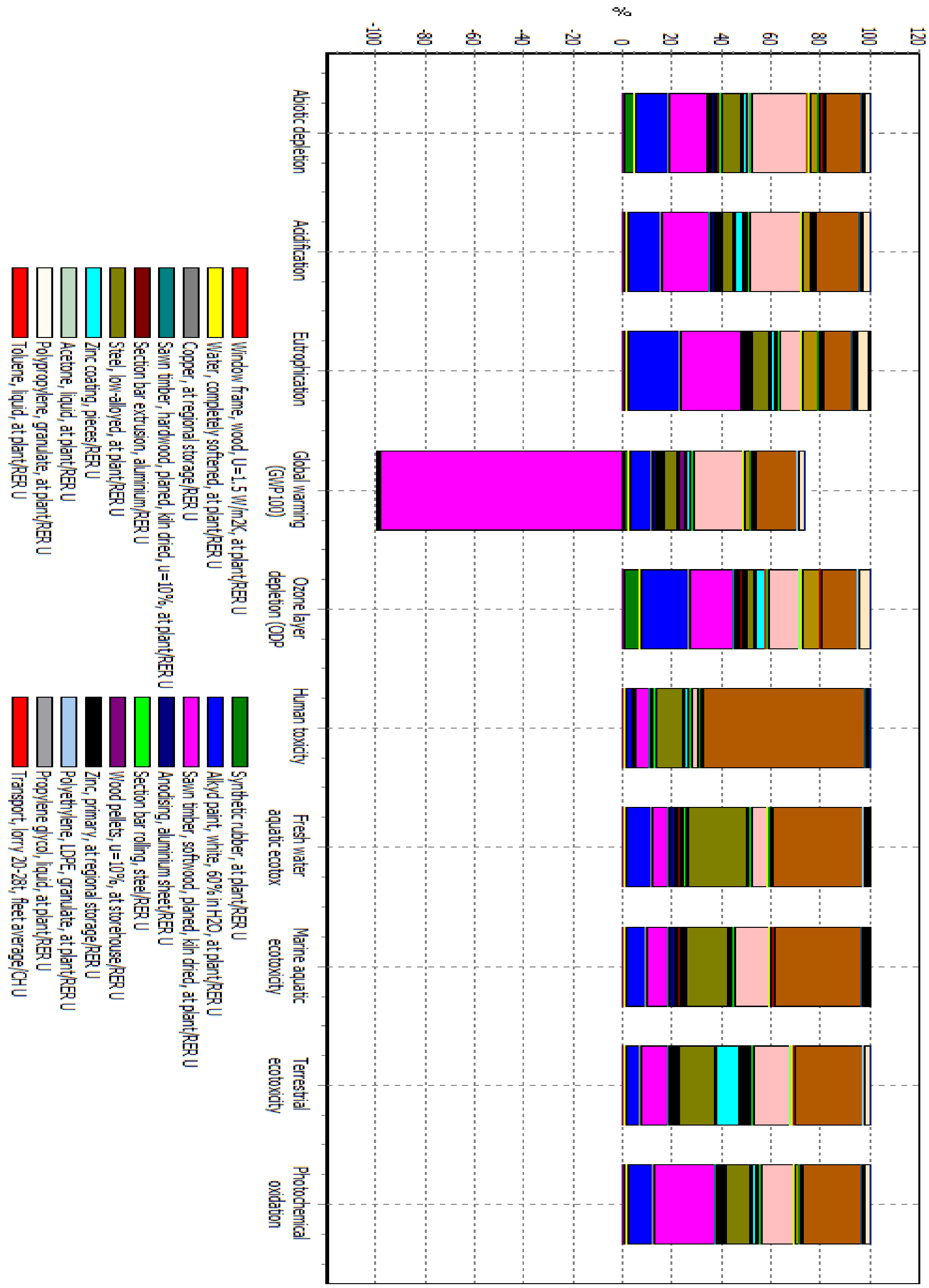


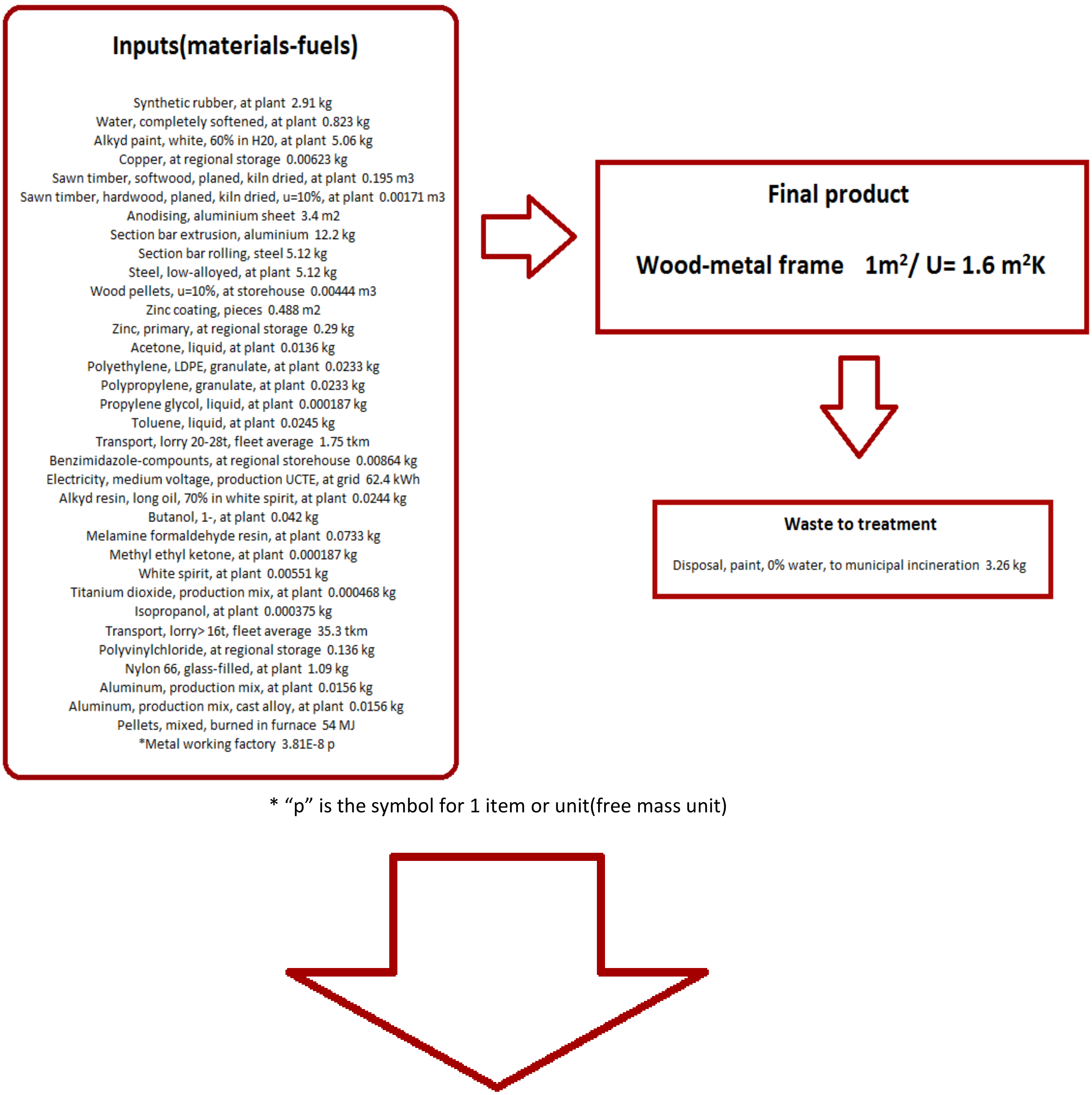
Figure 5.12.Input data (materials-fuels) contribution to impact categories (midpoints) for the production of wooden frame.

5.4. WOOD-METAL FRAME

Timber frames may be combined with other materials, mainly a metal (aluminium, steel etc), in order to improve the overall window properties by mixing their characteristics. Steel today is a very common material (metal-alloy), used for many purposes. It is widely known in construction sector among others, as it is highly durable, flexible and cheap compared to other metals. 90% of steel production is composed simply by iron and carbon with some additives of other elements (manganese, chromium, nickel etc), giving those special properties to the final alloy. Cladding with metal the exterior face of the frame, aims to protect the wood underneath ending with a more efficient product. This way protects frame against corrosive attacks, maximizing the useful life of the window and minimizing the maintenance obligations of timber.

Figure. 5.13 Aluminum-clad wooden frame

This dataset describes all the processes and material inputs needed to produce a wood-metal (steel) window frame with 1 m2 visible area, weighting 83.4 kg. Included processes are timber sawing, varnishing (primer, solvents, paint), section bar rolling for steel fittings, joining, fitting, all the road transport at different production phases and the disposal of the paint remains. The production process for $1m^2$ of wood-metal frame with U value equal to $1.6W/m^2K$, the materials used and the characterized results are shown in the following flowchart (Figure 5.13).



* “p” is the symbol for 1 item or unit(free mass unit)

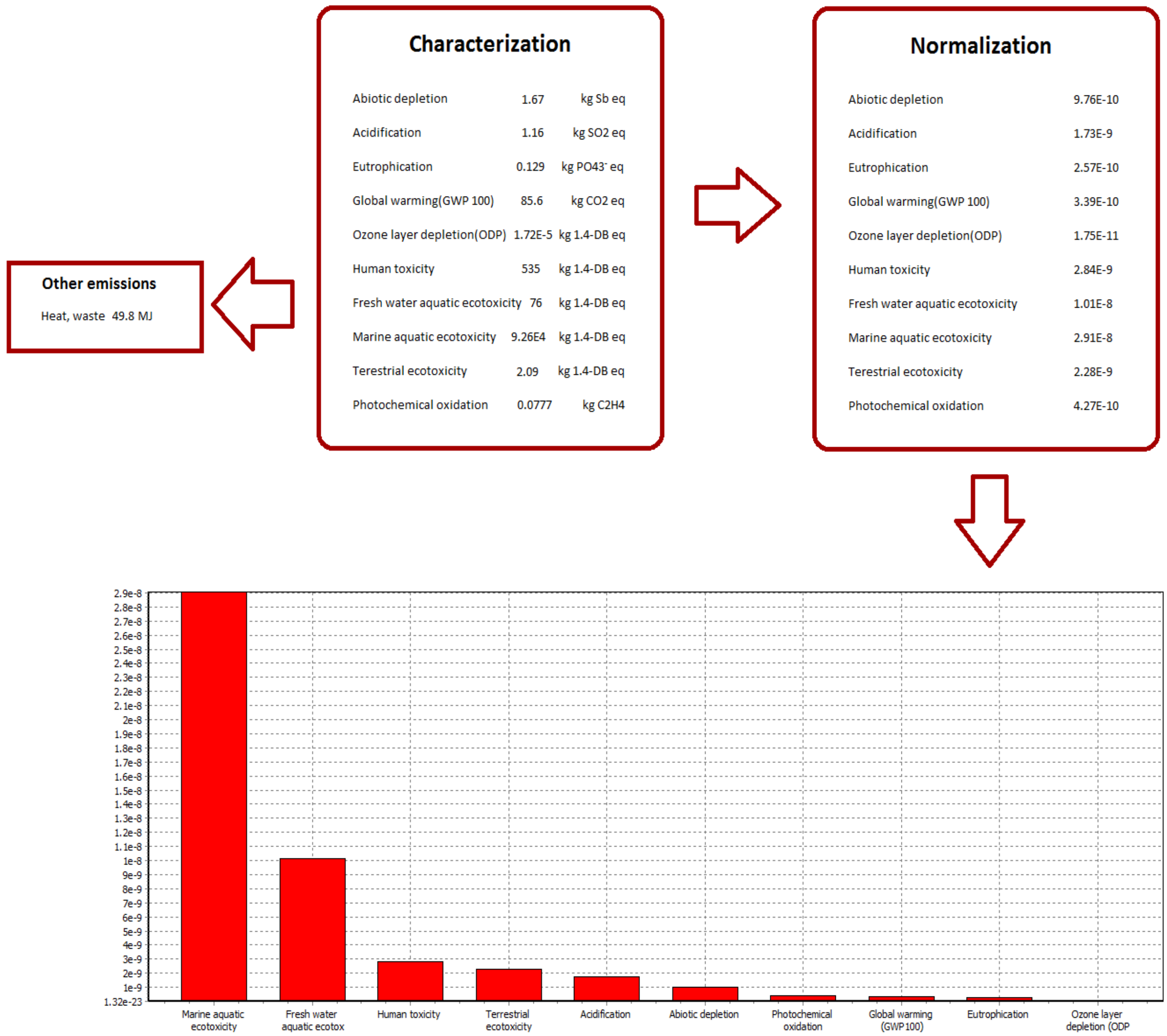


Figure 5.14. Flowchart and magnitude to impact categories per m^2 of wood-metal frame

According to the normalized results, emissions from wood-metal production significantly increase marine aquatic ecotoxicity compared to the reference state standards(CML2 baseline/ Netherlands 1997) used by the assessment method. On the other hand, ozone layer depletion is far less than the level of the benchmark.

Next follows the graph(figure 5.15) representing the partial share of inputs to the midpoint categories. The main two materials, softwood and steel alloyed as well as aluminium cast alloy are the major contributors.

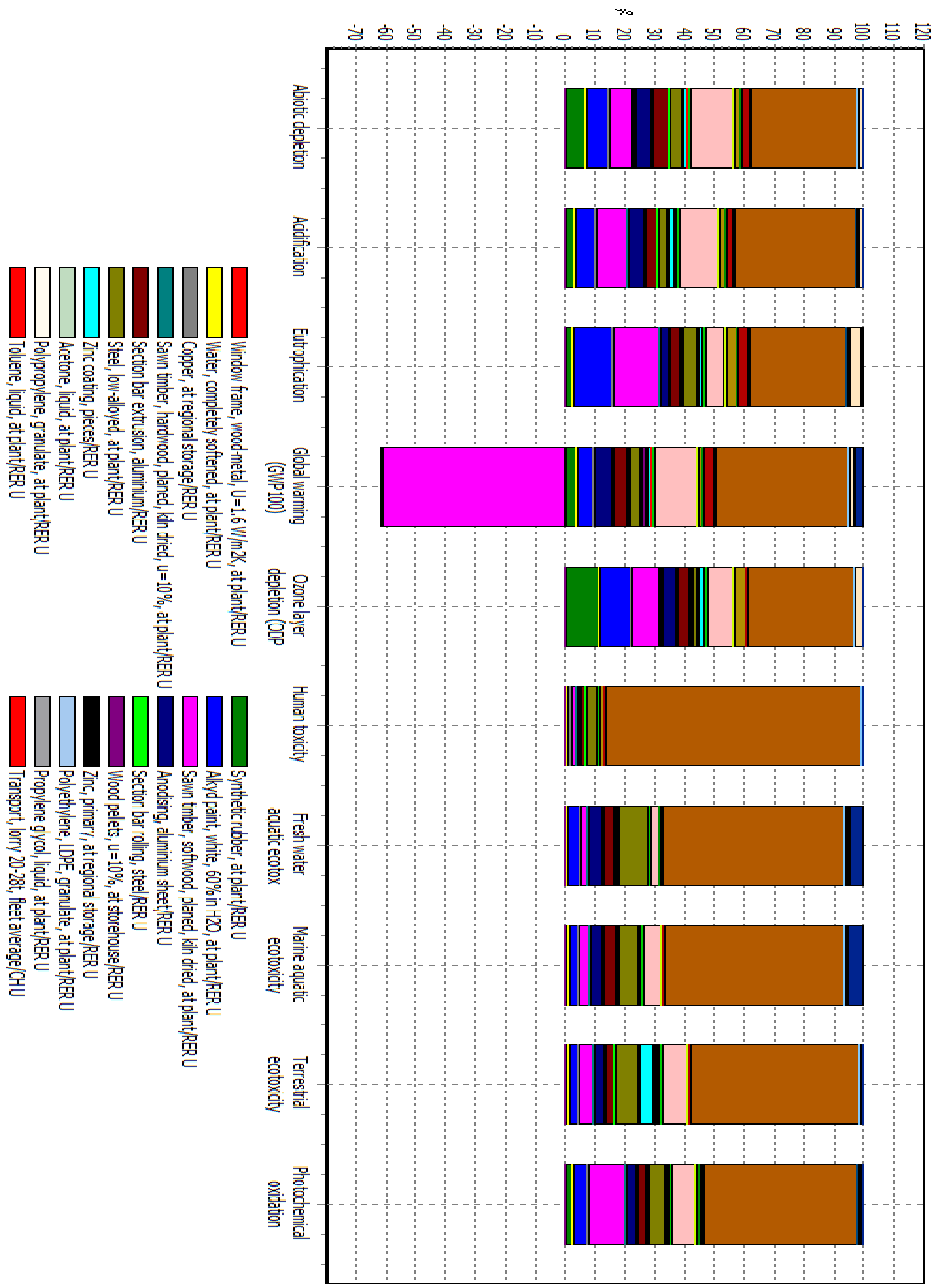


Figure 5.15.Input data (materials-fuels) contribution to impact categories (midpoints) for the production of wood-metal frame.

5.5. WINDOW FRAMES COMPARISON

After identifying inputs-outputs and their contribution to each impact category for every frame material respectively, a comparison among frames is performed to better illustrate the relevant significance in each category and in total. In general, aluminum frame (blue) is the dominant contributor while manufacturing of wooden frame (red) is the least emitted process. PVC frame(yellow) and wood-metal frame (green) are alternating the second and third place having almost the same implications.
After the normalization of the results and compared to a reference situation (Netherlands 1997) as it was described in goal and scope chapter, marine aquatic ecotoxicity is the most disordered category for all frame-cases. Figures 5.5a and 5.5b below give the characterized and normalized results in graphs to reach relative conclusions.

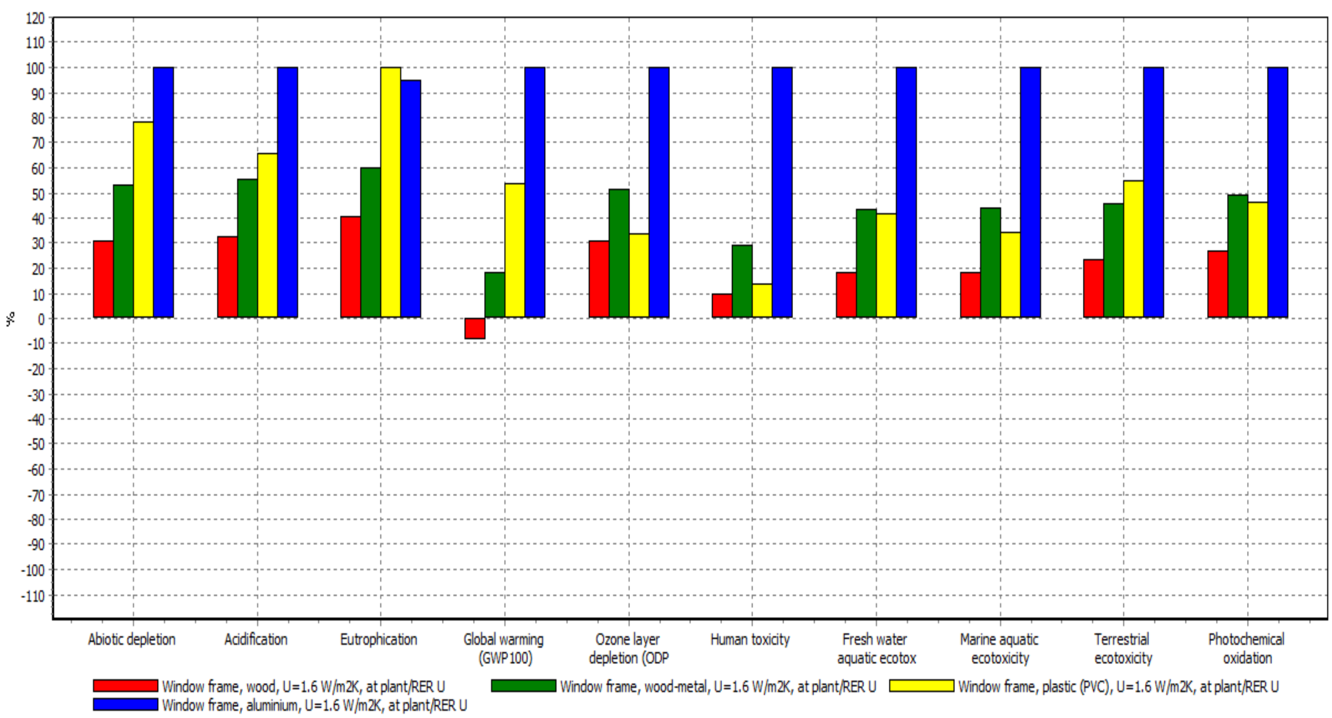


Figure 5.5a Comparison of characterized results between aluminum, wooden, PVC and wood-metal frame.

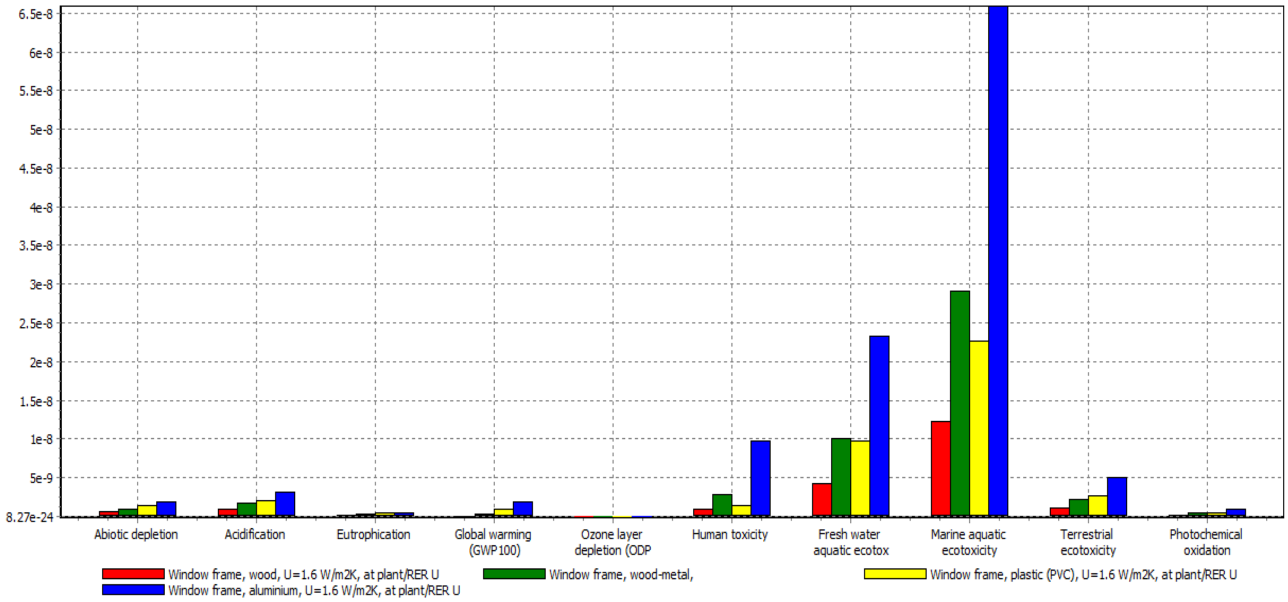


Figure 5.5b Comparison of normalized results between aluminum, wooden, PVC and wood-metal frame.

6. Environmental performance of glazing

The last chapter of the environmental assessment is applied on glass manufacturing. Even though glass material is common to all four window types and the energy requirements to be produced are the same for each case-frame, to depict the relative causation of window's subassemblies, a material analysis with the related production processes was conducted.
The dataset used describes all input materials and processes followed to produce a double-glazed unit of $1.06m^2$ that corresponds to $1m^2$ visible area. The mass of glass was estimated to be 20 kg in the final product, while the U value of the produced double-glazed unit is $1.1W/m^2K$.
In this thesis, the focus is directed in the partial life cycle of the product, from resource extraction to the factory gate(cradle to gate), followed by the relative impact categories.

6.1. GLAZING UNIT

Glazing [12] refers to the transparent element part of the window. Glazing is mounted in the window with the assistance of glazing putty and a frame which supports the glass and holds it in place. Historically, windows were single glazed, with a single pane of glass. Today, there are a number of options for window glazing. Double or triple glazed windows create more insulation, making a structure more energy efficienct by reducing heat loss through the windows. Glass can also be tinted to keep out sunlight, coated in a clear film which increases energy efficiency, and otherwise treated to make windows more efficient.
The most familiar type of glass, used for centuries in windows and drinking vessels, is soda-lime glass, composed of about 75% silica (SiO_2) plus Na_2O, CaO, and several minor additives.
Window and glazing choices should be considered holistically. Once the design team and owner agree on the design problem, window and glazing options can be evaluated. Ultimately, the optimum choice of window and glazing systems will depend on many factors including the building use type, the local climate, utility rates, and building orientation.

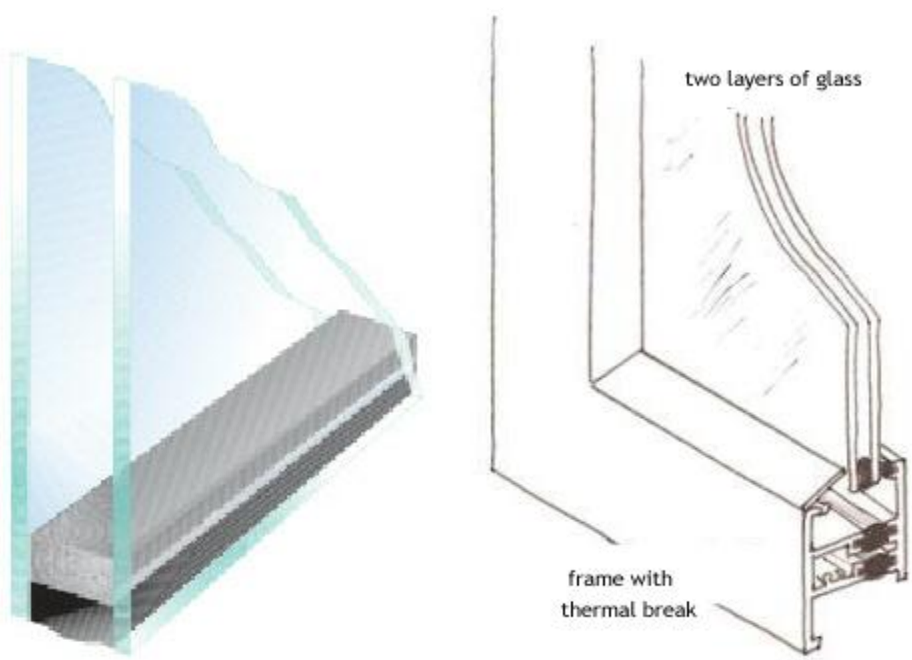
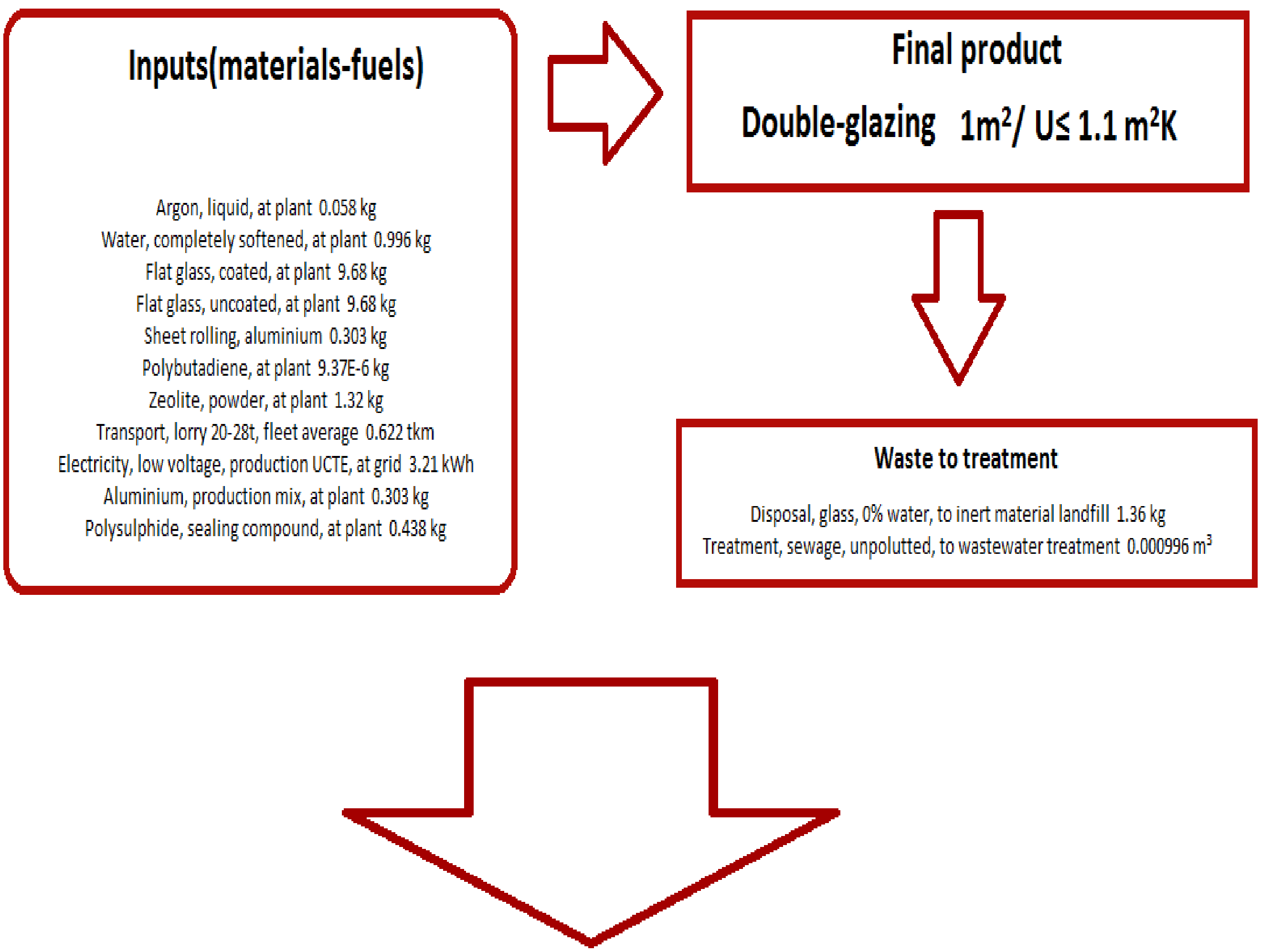


Figure 6.1. Double-glazed window.

Other studies have reported the energy content per kg of produced sheet glass to be from 13 MJ/kg to 20MJ/ kg, highly depending on the energy mix used and the processes followed. According to Greek manufacturer, an energy content of 15MJ/kg is considered representative for the aims of this study.
This dataset describes the processes included in the production of 1.06m2 (corresponding to 1m2 visible area) double glazing (2-IV) with a U-value below 1.1 W/m^2K, that can be used in the building sector. 1 m2 visible glazing area has a final weight of 20 kg and according to European company a total energy content of 300MJ per unit. Except materials and production processes in this dataset, disposal of waste water, production wastes and transportation are also included. The following flowchart (figure 6.2), corresponds to the specific production process of double-glazing. All inventory inputs are taken into account with SimaPro. Outputs are characterized results which represent impact categories and indicate the level of influence that glass production has to the environment.



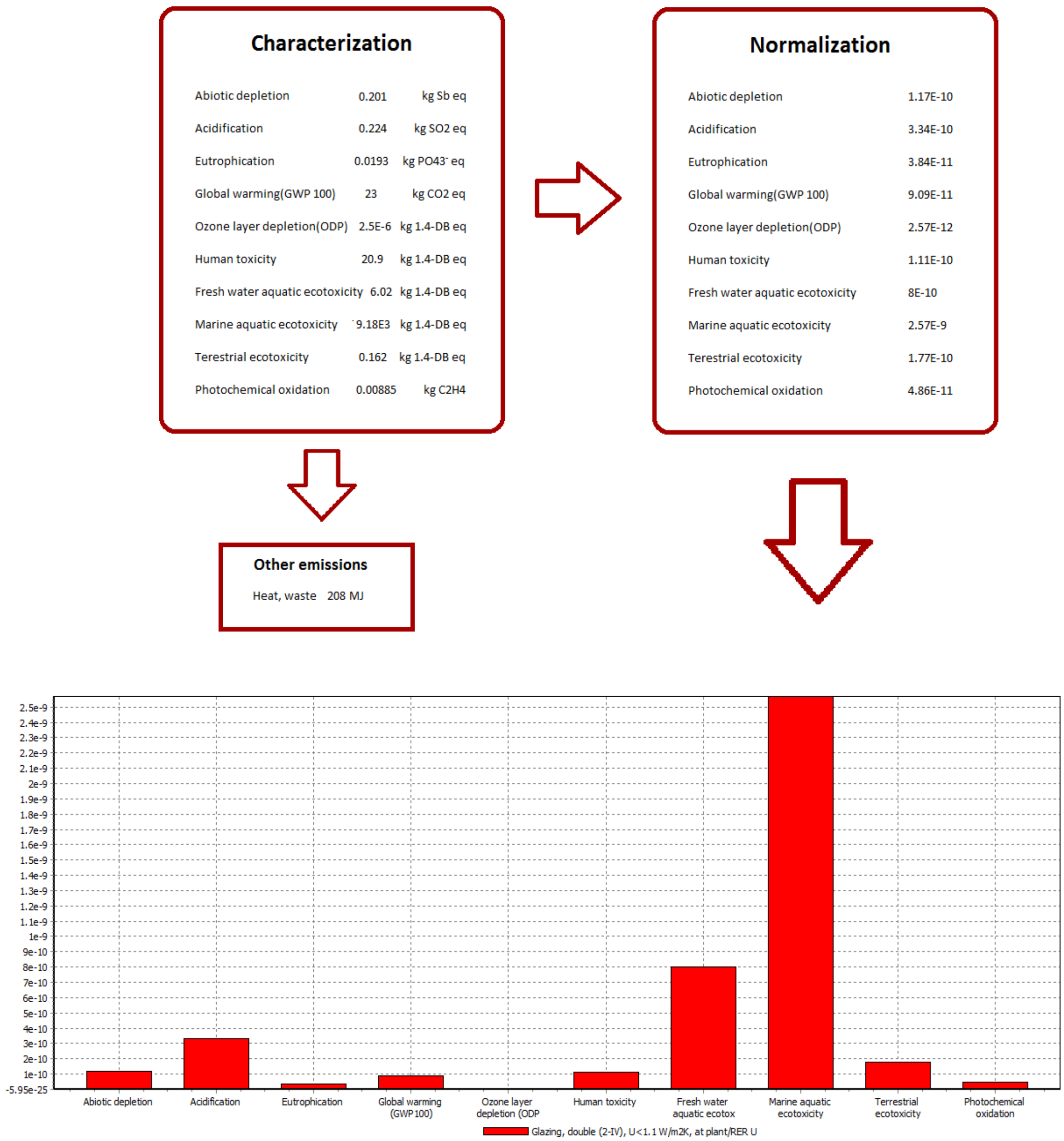


Figure 6.2. Flowchart and magnitude to impact categories per m^2 of double-glazing

The derived results, after being normalized and compared to the reference state (Netherlands 1997) used by this method, indicated that marine aquatic ecotoxicity is first in classification as the most affected category, while ozone layer depletion the last.

Finally, figure 6.3 corresponds to the share of inputs to each impact category respectively. Zeolite powder and flat glass coated as well as uncoated, are the three most environmentally hazardous contributors.

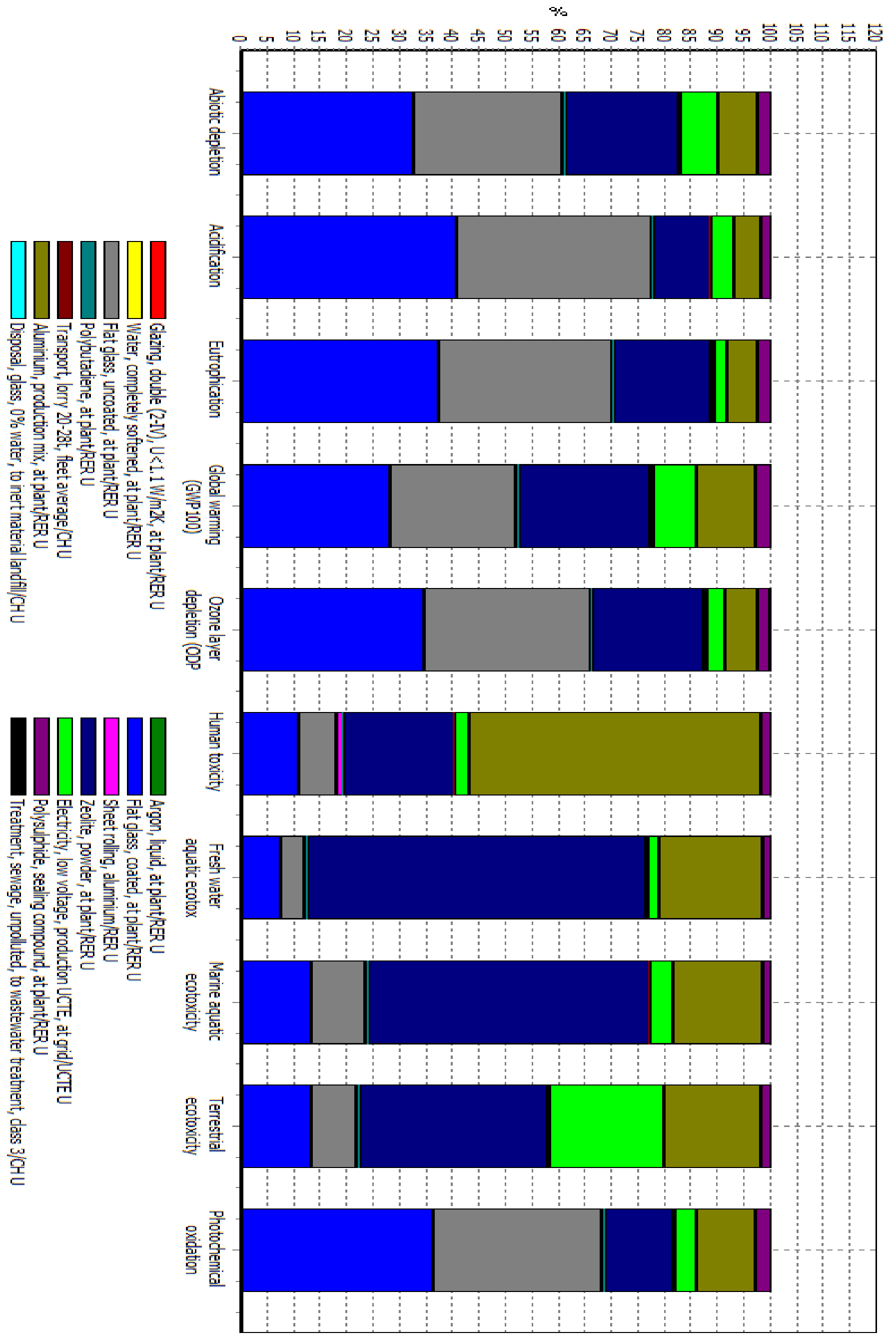


Figure 5.12.Input data (materials-fuels) contribution to impact categories (midpoints) for the production of double-glazing.

7. Conclusions

This dissertation research focused on the environmental performance of the most commonly used window-frames in construction sector by applying the life cycle analysis method. The impacts and differences associated with the production, final disposal and waste heat were identified to all four frame materials, all attributable to a standard reference casement window measuring 1m^2. The use-phase energy amount has been excluded from this analysis to not overshadow, and show the relative significance of manufacturing process.

The analysis is complemented with data and information in the sphere of Europe and in national level. In completing the LCI and LCIA, data sources and assumptions were taken in a way to overlap any possible lack of information as it was described in goal and scope of this research. The accuracy of model and data may influence to some extend the findings and results may differ from study to study.

The window systems under assessment were namely aluminum, PVC, wood-metal and metal frames followed by a standard unit of double-glazing. As in accordance to literature review, aluminum frames proved to cause the highest burden to the environment, dominating almost all impact categories except the one of eutrophication where PVC manufacturing contributes the most. The results indicate that timber frame was the least burden to environment, being the least polluted to all impact categories.

The cradle to gate emissions for the 1m^2 unit of double-glazing is considered common for all window frames and thus is not involved in the previous comparison.

Based in all LCA's that considered frame materials and after coming in touch with manufacturers, aluminum windows have the highest embodied energy regardless the portion of recycled aluminum use. This is mainly happening because of the complexity of aluminum processing which is highly energy intense. On the other hand and commonly acceptable for most of the studies, timber is the least energy intense material, fairly nominating as the frame with the least embodied energy. PVC and wood-metal frames are in between presenting a more average energy consumption to be processed than the alternatives.

Another aspect that should be further analyzed in the future is the inclusion of the use-phase comparison between different window cases in Greece, and to justify increased energy resource use and embodied energy in manufacturing, to compensate energy performance during occupancy. This way a more comprehensive picture of the whole life-cycle of windows may lead to more rational conclusions from decision-makers, with the most suitable and appropriate decisions in every case and for every possible scenario.

By observing the resulted data from this study, and having in mind the results of other relevant studies, it becomes perfectly conceivable the magnitude of influence that window manufacturing have to the environment and human health.

The most widely accepted way to improve the energy efficiency (embodied energy) and thus the overall environmental performance of the final product, is by utilizing a bigger portion of recyclable- recycled materials.

Other potential improvements under consideration that could reduce the environmental burdens to a more tolerable level, is the utilization of more energy efficient technologies by the window manufacturers, and the consisting research in this section for less energy intensive processes. To make this happen, the right incentives should be given to manufacturers that will further challenge them on a constant base in this field.

Another potential improvement, generally proposed from most of the studies, is the extension of the service life of the installed windows, which in turn reduces the need of replacement and thus the impacts from manufacturing, resource extraction and disposal.

By extending the service life of a window, which maintains on a good level its characteristics and properties, we reduce fossil fuel usage and minimize all related impact categories arisen from that consumption.

So, there are ways to reduce or even restrict emissions under a certain level if the state or other agents give the correct incentives to manufactures, on the way to this course.

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